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Island Press is the only nonprofit organization in the United States whose principal purpose is the publication of books on environmental issues and natural resource management. We provide solutions-oriented information to professionals, public officials, business and community leaders, and concerned citizens who are shaping responses to environmental problems.

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About SCOPE

The Scientific Committee on Problems of the Environment (SCOPE) was established by the International Council for Science (ICSU) in 1969. It brings together natural and social scientists to identify emerging or potential environmental issues and to address jointly the nature and solution of environmental problems on a global basis. Operating at an interface between the science and decision-making sectors, SCOPE’s interdisciplinary and critical focus on available knowledge provides analytical and practical tools to promote further research and more sustainable management of the Earth’s resources. SCOPE’s members, forty national science academies and research councils and twenty-two international scientific unions, committees, and societies, guide and develop its scientific program.
The Global Carbon Cycle
The Scientific Committee on Problems of the Environment (SCOPE)

SCOPE Series

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SCOPE 61: Interactions of the Major Biogeochemical Cycles: Global Change and Human Impacts, edited by Jerry M. Melillo, Christopher B. Field, and Bedrich Moldan

Contents

List of Figures, Tables, and Boxes ........................................ xx
Foreword ........................................................................... xx
Preface ............................................................................... xx
Acknowledgments ................................................................. xx

1. The Global Carbon Cycle: Integrating Humans,
   Climate, and the Natural World ................................... 00
   Christopher B. Field, Michael R. Raupach, and Reynaldo Victoria

Part I: Crosscutting Issues

2. Current Status and Past Trends
   of the Global Carbon Cycle ........................................ 00
   Christopher L. Sabine, Martin Heimann, Paulo Artaxo, Dorothee
   C. E. Bakker, Chen-Tung Arthur Chen, Christopher B. Field,
   Nicolas Gruber, Corinne Le Quéré, Ronald G. Prinn, Jeffrey E.
   Richey, Patricia Romero Lankao, Jayant A. Sathaye, and Riccardo
   Valentini

3. The Vulnerability of the Carbon Cycle
   in the 21st Century: An Assessment
   of Carbon-Climate-Human Interactions ....................... 00
   Nicolas Gruber, Pierre Friedlingstein, Christopher B. Field,
   Riccardo Valentini, Martin Heimann, Jeffrey E. Richey, Patricia
   Romero Lankao, E.-Detlef Schulze, and Chen-Tung Arthur Chen

4. Scenarios, Targets, Gaps, and Costs ........................... 000
   Jae Edmonds, Fortunat Joos, Nebojsa Nakicenovic, Richard G.
   Richels, and Jorge L. Sarmiento
5. A Portfolio of Carbon Management Options ........................................000
Ken Caldeira, M. Granger Morgan, Dennis Baldocchi, Peter G.
Brewer, Chen-Tung Arthur Chen, Gert-Jan Nabuurs, Nebojsa
Nakicenovic, and G. Philip Robertson

6. Interactions between CO₂ Stabilization Pathways
and Requirements for a Sustainable Earth System ..............................000
Michael R. Raupach, Josep G. Canadell, Dorothee C. E. Bakker,
Philippe Ciais, Maria José Sanz, Jingyun Fang, Jerry M. Melillo,
Patricia Romero Lankao, Jayant A. Sathaye, E.-Detlef Schulze, Pete
Smith, and Jeff Tschirley

Part II: Overview of the Carbon Cycle

7. A Paleo-Perspective on Changes
in Atmospheric CO₂ and Climate .....................................................000
Fortunat Joos and I. Colin Prentice

8. Spatial and Temporal Distribution
of Sources and Sinks of Carbon Dioxide ..........................................000
Martin Heimann, Christian Rödenbeck, and Manuel Gloor

9. Non-CO₂ Greenhouse Gases ............................................................000
Ronald G. Prinn

10. Climate–Carbon Cycle Interactions ..................................................000
Pierre Friedlingstein

11. Socioeconomic Driving Forces of Emissions Scenarios .................000
Nebojsa Nakicenovic

Part III: The Carbon Cycle and the Oceans

12. Natural Processes Regulating
the Ocean Uptake of CO₂ ...............................................................000
Corinne Le Quéré and Nicolas Metzl

13. Variability and Climate Feedback Mechanisms
in Ocean Uptake of CO₂ .................................................................000
Jeffery B. Greenblatt and Jorge L. Sarmiento
Part IV: The Carbon Cycle and the Land

14. A Primer on the Terrestrial Carbon Cycle: What We Don't Know But Should ........................................... 000
   Jonathan A. Foley and Navin Ramankutty

15. Geographic and Temporal Variation of Carbon Exchange by Ecosystems and Their Sensitivity to Environmental Perturbations ........................................... 000
   Dennis Baldocchi and Riccardo Valentini

16. Current Consequences of Past Actions: How to Separate Direct from Indirect ........................................... 000
   Gert-Jan Nabuurs

Part V: The Carbon Cycle and Land-Ocean Margins

3. Pathways of Atmospheric CO₂ through Fluvial Systems ........................................... 000
   Jeffrey E. Richey

3. Exchanges of Carbon in the Coastal Seas ........................................... 000
   Chen-Tung Arthur Chen

Part VI: Humans and the Carbon Cycle

19. Pathways of Regional Development and the Carbon Cycle ........................................... 000
   Patricia Romero Lankao

20. Social Change and CO₂ Stabilization: Moving away from Carbon Cultures ........................................... 000
   Louis Lebel

21. Carbon Transport through International Commerce ........ 000
   Jeff Tschirley and Géraud Servin

Part VII: Purposeful Carbon Management

22. Near- and Long-Term Climate Change Mitigation Potential ........................................... 000
   Jayant A. Sathaye
Jae Edmonds

24. International Policy Framework on Climate Change: Sinks in Recent International Agreements .........................000 
Maria José Sanz, E.-Detlef Schulze, and Riccardo Valentini

25. A Multi-Gas Approach to Climate Policy .........................000 
Alan S. Manne and Richard G. Richels

26. Storage of Carbon Dioxide by Greening the Oceans? ........000 
Dorothee C. E. Bakker

27. Direct Injection of CO₂ in the Ocean .........................000 
Peter G. Brewer

28. Engineered Biological Sinks on Land .........................000 
Pete Smith

29. Abatement of Nitrous Oxide, Methane, and the Other Non-CO₂ Greenhouse Gases: The Need for a Systems Approach .........................000 
G. Philip Robertson

List of Contributors .................................................................000
SCOPE Series List .................................................................000
SCOPE Executive Committee ....................................................000
Index .................................................................000
List of Figures, Tables, and Boxes

Figures

1.1. (a) Schematic representation of the components of the coupled carbon-climate-human system and the links among them. (b) Two complementary perspectives on human drivers of carbon emissions. 00
1.2. Effects of inertia in the coupled carbon-climate-human system. 00
1.3. The energy gap, showing the growing difference between the emissions projected in a widely used scenario (IS92a) and the emissions required to stabilize the atmospheric CO$_2$ at 550 ppm. 00
2.1. The current carbon cycle, showing (a) the globe, plus detailed views for (b) the oceans, and (c) the land. 00
2.2. The distribution of sources for the world energy system in 2000. 00
2.3. Mean annual net air-sea CO$_2$ flux for 1995. 00
2.4. Total column inventory of anthropogenic CO$_2$ in the oceans. 00
2.5. A summary of the sources, quantities, lifetimes, and consequences of carbon containing non-CO$_2$ gases in the atmosphere. 00
2.6. Historical composition of the world energy system, in (A) percent contributions and (B) energy contributions in EJ. 00
3.1. Cumulative fossil-fuel emissions and their redistribution among the three major reservoirs of the global carbon cycle over the period from 1920 to 2100 as modeled by two Earth system models. 00
3.2. Vulnerability of the carbon pools in the 21st century. 00


4.2. Characteristics of SRES scenarios.

4.3. Anthropogenic CO2 emissions for (a) fossil fuels and (b) land use change.

4.4. Global primary energy requirements since 1850 and in the IPCC SRES scenarios to 2100 in EJ per year.

4.5. Effects of energy intensity improvements on energy demands in SRES illustrative scenarios.

4.6. Range of non-carbon-emitting energy supply in SRES marker scenarios.

4.7. Global carbon dioxide emissions in billion tons of carbon (PgC) per year since 1850 to present, emissions trajectories for the Six SRES Illustrative scenarios, 350, 450, 550, 650, and 750 ppm.

4.8. WRE CO2 emissions trajectories for five alternative CO2 concentrations.

4.9. The “Gap” for five alternative CO2 concentrations.

4.10. Comparison of emissions trajectories consistent with various atmospheric CO2 concentrations.

4.11. Relationship between present discounted costs for stabilizing the concentrations of CO2 in the atmosphere at alternative levels.

4.12. (a) Allowed carbon emission for the WRE550 pathway where atmospheric CO2 is stabilized at 550 ppm as simulated with the Bern CC model.

4.13. Impact of a possible collapse of the formation rate of North Atlantic Deep Water (NADW) on the oceanic carbon uptake, and hence the carbon emission allowance to meet a stabilization target.

5.1. Cost of electricity presented as function CO2 emissions per unit energy produced.

5.2. Representation of model results for direct injection of carbon into the ocean at three depths under two different boundary conditions.

6.1. Evolution of the terms in equation (3) over the next century from their current values, under simple growth assumptions.
6.2. Effects of economic, environmental and social-institutional factors on the mitigation potential of a carbon management strategy.

6.3. Characteristics of the main SRES marker scenario families.

7.1. The evolution of proxies for local temperature in Greenland and Antarctica and the atmospheric concentration of the two greenhouse gases CO$_2$ and CH$_4$ over the last glacial-interglacial transition.

7.2. The evolution of atmospheric CO$_2$ concentration and Greenland and Antarctic temperature, as indicated by $\Delta^{18}$O, during the period from 70 ka BP to 20 ka BP.

7.3. Holocene variations in atmospheric CO$_2$ concentration, from measurements on air entrapped in ice from Taylor Dome, Antarctica, and from Dome Concordia.

7.4. Relationship between Northern Hemisphere (NH) surface temperature change, climate–carbon cycle feedbacks, and variations in atmospheric CO$_2$.

8.1. Interannual variability of global ocean-atmosphere and land-atmosphere CO$_2$ fluxes.

8.2. Annual mean atmospheric CO$_2$ concentration difference between the Mauna Loa and the South Pole station shown against interhemispheric difference in annual fossil-fuel emissions.

8.3. Annual mean latitudinal land-ocean breakdown of non-fossil-fuel carbon sources as determined in the TRANSCOM inversion intercomparison study of Gurney et al. 2002.

8.4. (a) Total net surface-air CO$_2$ flux and (b) net non-fossil-fuel surface-air flux inferred from the atmospheric inversion average July 1995–June 2000.

8.5. Time series of surface-atmosphere fluxes integrated over five continental areas and over three oceanic latitudinal bands.

8.6. Time series of anomalous non-fossil-fuel net land-atmosphere flux from the inversion compared with fire counts compiled by the European Space Agency, both aggregated over two continental areas.

10.1. Global feedbacks between the carbon cycle and the climate system.

10.2. Cumulative carbon budgets for the IPSL and Hadley coupled simulations.

11.1. Global carbon emissions: Historical development and scenarios.
11.2. Global population projections: Historical development and scenarios.

11.3. Global economic development measured by gross world product (GWP) measured at market exchange rates: Historical development and scenarios.

11.4. GWP and population growth: Historical development and scenarios.

11.5. Global primary energy requirements: Historical development and scenarios.

11.6. Primary energy intensity versus GDP per capita measured at market exchange rates: Regional historical developments.

11.7. Global decarbonization of primary energy: Historical development and scenarios.


12.1. Sea-air CO₂ flux by latitude band.


12.3. Global mean current inventory and potential maximum of anthropogenic carbon for an atmospheric CO₂ concentration of 368 ppm.

12.4. Regional estimates of air-sea CO₂ fluxes based on ocean tracer inversion and forward models, atmospheric inversions, and ocean measurements.


13.3. Marginal airborne fraction vs. CO₂ release.


14.3. A highly simplified model of the terrestrial carbon cycle.

15.1. Relation between carbon content in the top meter of soil and mean annual temperature.

15.2. Geographic distribution of the dominant environmental factors governing NPP.

15.3. Seasonal variation in net CO₂ exchange of a temperate deciduous forest.
xvi | List of Colorplates, Figures, Tables, and Boxes

19.5. Local governmental revenue and expenditures (1998).

20.1. A simple conceptual framework for various social structures and processes influencing the global carbon cycle.


22.1. Actual per capita CO$_2$ emissions and per capita CO$_2$ emissions indexed to the ratio of 1971 GDP (1990 US$1,000) to 1971 CO$_2$ emissions for selected countries.
22.2. Projections of (a) GDP losses and (b) marginal cost in Annex B countries in 2010 from global models.
22.3. Rate of change in (a) energy intensity, and (b) carbon intensity, historically achieved levels (1860–1990).

25.1. Incremental value of emission rights for (a) carbon, (b) CH$_4$, and (c) N$_2$O, 2010–2100 (alternative temperature ceilings).
25.2. Prices of a ton of (a) CH$_4$ and (b) N$_2$O relative to carbon (alternative temperature ceilings).
25.3. Prices of a ton of (a) CH$_4$ and (b) N$_2$O relative to carbon (constraint on absolute decadal temperature change).
25.4. Prices of a ton of (a) CH$_4$ and (b) N$_2$O relative to carbon when the objective is balancing costs and benefits.
26.1. Seasonally averaged concentrations of nitrate and chlorophyll in oceanic surface waters with contours at 2 µmol l⁻¹ and 0.5 µmol l⁻¹ intervals, respectively.

26.2. Parameters inside and outside the iron-fertilized waters (or “patch”) in the Southern Ocean Iron RElease Experiment.

27.1. The phase behavior of CO₂ in seawater, showing the gas-liquid and hydrate phase boundaries with a typical in situ P-T profile.

27.2. A “frost heave” of CO₂ hydrate on the seafloor at 3,600 m depth resulting from massive hydrate formation.

27.3. A 56 l carbon-fiber-wound CO₂ delivery system installed on ROV Tiburon, showing end cap with gauges, delivery pumps on top, and valves to the left.

27.4. A sketch of a deep-sea CO₂ enrichment experimental site designed to investigate the response of marine organisms to locally elevated CO₂ levels.

27.5. The pH signals recorded at distances of 1 m, 5 m, and 50 m from a CO₂ source placed on the seafloor.

28.1. Relationships between reported carbon sequestration potentials depending on the number and type of constraints considered.

28.2. Illustrative graph showing the possible time course of sink development.


29.2. Estimated global budgets of the anthropic sources of CH₄ and N₂O.

29.3. Seasonal CH₄ emission in lowland rice as a function of grain yield.

Tables

2.1. The global carbon budget.

2.2. Plant carbon, soil carbon, and net primary production in the world's major biomes.

3.1. Summary of pools and their vulnerability over the next 20 years and over the course of the 21st century.

3.2. Summary of marine carbon cycle feedbacks.

4.1. The gap for the six SRES illustrative scenarios for atmospheric CO₂ concentrations ranging from 450 ppm to 750 ppm (PgC/year).
4.2. The gap for the six SRES illustrative scenarios for atmospheric CO₂ concentrations ranging from 450 ppm to 750 ppm (EJ/year).

4.3. Allowed carbon emissions for WRE 450 and WRE 750 stabilization pathways.

4.4. Impact of climate feedback on carbon sinks and global warming in the Hadley and IPSL simulations.

5.1. Categorization of mitigation options by timescale to achieve a significant proportion of possible reductions and by potential magnitude of CO₂ equivalent impact on radiative forcing.

5.2. Magnitude of R&D needed driven by CO₂ mitigation needs.

5.3. Estimates of storage capacity of geologic reservoirs compiled by J. Edmonds.

5.4. Potential for non-CO₂ greenhouse gas abatement and biosphere carbon storage.

6.1. Current (1990–1999) global average values for terms in the global carbon budget and the quantities \( P, g_e, f, i \).

6.2. Assessment of positive and negative climate, economic, environmental, and sociocultural impacts associated with mitigation strategies.

6.3a. Scenario drivers taken from the SRES scenarios and total carbon gap from Chapter 4, this volume.

6.3b. Increase in food demand under each scenario.

6.3c. Impacts of scenarios on the pressure on land for food production.


9.2. Current global emissions of non-CO₂ greenhouse gases expressed as equivalent amounts of carbon (Ceq) in CO₂ using GWPs with a 100-year time horizon.

12.1. Estimates of mean ocean CO₂ uptake from various methods and recent time periods.


13.2. Cumulative ocean uptake of CO₂ due to different climate-induced feedback effects.

13.3. Biological effects on cumulative ocean uptake of CO₂.
13.4. Studies of THC slowdown under global warming scenarios. 00
14.1. Estimates of global budget of anthropogenic carbon emissions, as reported by the IPCC third assessment report. 00
14.2. Comparison of global budget of anthropogenic carbon emissions for the 1980s using Houghton (1999) land use emissions estimates. 00
14.3. Comparison of global budget of anthropogenic carbon emissions for the 1980s, using two different estimates of land use emissions. 00
14.4. Breakdown of the terrestrial carbon budget for the 1980s, based on the CCMLP simulations. 00
18.1. Fluxes relevant to continental margins 00
21.1. SITC framework for national export and import. 00
21.2. Selected agricultural and forest product trade data availability. 00
21.3. Carbon exports and imports by continent for 2000. 00
21.4. Volume and value of cereals, paper, and wood products exports by continent for 2000. 00
21.5. Carbon exports from region to region for 2000. 00
22.1. Estimates of potential global greenhouse gas emission reductions in 2010 and 2020. 00
22.2. Estimates of potential global greenhouse gas emission reductions in 2010: Land use, land use change, and forestry. 00
24.1. Major conferences on global climate change. 00
25.1. Methane emissions, 1990. 00
25.2. Potential sink enhancement in 2010 at a marginal cost of US$100 per ton of carbon. 00
25.3. Anthropogenic nitrous oxide emissions, 1990. 00
26.1. The amount of added iron (Fe) and the observed drawdown of dissolved inorganic carbon (DIC) in the mixed layer during three iron fertilization experiments. 00
29.1. Global warming potentials (mass basis) for major greenhouse gases over different time periods. 00
29.2. Annual fluxes of CH\textsubscript{4} and N\textsubscript{2}O in carbon-equivalent units. 00
29.3. Sources of greenhouse gas flux in agricultural and forest systems at a U.S. Midwest site.

Boxes

28.1. Management options to enhance terrestrial carbon sinks

Appendixes

21.1 Selected definitions.
21.2 Crop carbon ratios.
21.3 Top importers and exports of cereals, paper products, and wood products, 2000.
21.4 Country groupings.
21.5 Export and imports from reporter to partner, 2000.
Foreword

The Scientific Committee on Problems of the Environment (SCOPE) publishes this book as the second in a series of rapid assessments of the important biogeochemical cycles that are essential to life on this planet. SCOPE’s aim is to make sure that experts meet on a regular basis to discuss and summarize recent advances within disciplines and evaluate their possible significance in understanding environmental problems and potential solutions. The SCOPE rapid assessment series attempts to ensure that the information so generated is published and made available within a year from the date of the synthesis. These assessments provide timely, definitive syntheses of important issues for scientists, students, and policy makers.

The present volume is intended to be a successor to SCOPE carbon books of the 1970s and 1980s and to complement recent Intergovernmental Panel on Climate Change reports on the scientific basis of climate change, the impacts of climate change, and the potential for mitigation of climate change. This volume’s main concept is that the carbon cycle, climate, and humans work together as a single system. This type of system-level approach focuses the science on a number of issues that are almost certain to be important in the future. It should provide a timely examination of the practical consequences of this knowledge being used in the sustainability of ecosystems affected by humans.

This synthesis volume is a joint project of two bodies sponsored by the International Council of Science (ICSU): SCOPE and the Global Carbon Project (GCP). SCOPE is one of twenty-six interdisciplinary bodies established by the ICSU to address cross-disciplinary issues. In response to emerging environmental concerns, the ICSU established SCOPE in 1969 in recognition that many of these concerns required scientific input spanning several disciplines represented within its membership. Representatives of forty member countries and twenty-two international, disciplinary-specific unions, scientific committees, and associates currently participate in the work of SCOPE, which directs particular attention to developing countries. The mandate of SCOPE is to assemble, review, and synthesize the information available on environmental changes attributable to human activity and the effects of these changes on humans; to assess and evaluate methodologies for measuring environmental parameters; to provide an intel-
ligence service on current research; and to provide informed advice to agencies engaged
in studies of the environment.

The recently formed Global Carbon Project is a shared partnership between the
International Geosphere-Biosphere Programme (IGBP), the International Human
Dimensions Programme on Global Environmental Change (IHDP), and the World
Climate Research Programme (WCRP). The attention of the scientific community, pol-
icy makers, and the general public increasingly focuses on the rising concentration of
 greenhouse gases, especially carbon dioxide (CO$_2$), in the atmosphere and on the car-
bon cycle in general. Initial attempts, through the United Nations Framework Con-
vention on Climate Change and its Kyoto Protocol, are underway to slow the rate of
increase of greenhouse gases in the atmosphere. These societal actions require a scien-
tific understanding of the carbon cycle and are placing increasing demands on the
international science community to establish a common, mutually agreed knowledge
base to support policy debate and action. The Global Carbon Project aims to meet this
challenge by developing a complete picture of the global carbon cycle, including both
its biophysical and human dimensions together with the interactions and feedbacks
between them.

John W. B. Stewart, Editor-in-Chief

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The RAP for the carbon cycle was supported by funds from the A. W. Mellon Foundation, the National Science Foundation (U.S.), the National Aeronautics and Space Administration (U.S.), the National Oceanic and Atmospheric Administration (U.S.), the National Institute for Environmental Studies (Japan), and the European Union. Additional travel funds came from the Electric Power Research Institute. Thanks to Yoshiki Yamagata for help with funding from the National Institute for Environmental Studies and to Riccardo Valentini with for help with funding from the European Union. Additional travel funds came from the Electric Power Research Institute.

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The city of Ubatuba, Brazil, provided a stimulating and enjoyable venue for developing the ideas discussed in this volume. The Carnegie Institution of Washington and the Commonwealth Scientific and Industrial Research Organization (CSIRO) generously provided the time to let us steer this project.

Finally, it is a privilege to work with and share the excitement of scientific discovery with the community of carbon cycle researchers. Their dedication and insight help lay the foundations for a sustainable future.

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The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World

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1

The Carbon-Climate-Human System

It has been more than a century since Arrhenius (1896) first concluded that continued emissions of carbon dioxide from the combustion of fossil fuels could lead to a warmer climate. In the succeeding decades, Arrhenius’s calculations have proved both eerily prescient and woefully incomplete. His fundamental conclusion, linking fossil-fuel combustion, the radiation balance of the Earth system, and global climate, has been solidly confirmed. Both sophisticated climate models (Cubasch et al. 2001) and studies of past climates (Joos and Prentice, Chapter 7, this volume) document the link between atmospheric CO₂ and global climate. The basic understanding of this link has led to a massive investment in detailed knowledge, as well as to political action. The 1992 United Nations Framework Convention on Climate Change is a remarkable accomplishment, signifying international recognition of the vulnerability of global climate to human actions (Sanz et al., Chapter 24, this volume).

Since Arrhenius’s early discussion of climate change, scientific understanding of the topic has advanced on many fronts. The workings of the climate system, while still uncertain in many respects, are well enough known that general circulation models accurately reproduce many aspects of past and present climate (McAvaney et al. 2001). Greenhouse gas (GHG) emissions by humans are known with reasonable accuracy (Andres et al. 1996), including human contributions to emissions of greenhouse gases other than CO₂ (Prinn, Chapter 9, this volume). In addition, a large body of literature characterizes land and ocean processes that release or sequester greenhouse gases in the
context of changing climate, atmospheric composition, and human activities. Much of
the pioneering work on land and ocean aspects of the carbon cycle was collected in or
inspired by three volumes edited by Bert Bolin and colleagues and published by
SCOPE (Scientific Committee on Problems of the Environment) in 1979 (Bolin et al.

The Intergovernmental Panel on Climate Change (IPCC), established by the
United Nations as a vehicle for synthesizing scientific information on climate change,
has released a number of comprehensive assessments, including recent reports on the sci-
entific basis of climate change (Houghton et al. 2001), impacts of climate change
(McCarthy et al. 2001), and potential for mitigating climate change (Metz et al. 2001).
These assessments, which reflect input from more than 1,000 scientists, summarize the
scientific literature with balance and precision. The disciplinary sweep and broad par-
ticipation of the IPCC efforts are great strengths.

This volume is intended as a complement to the IPCC reports and as a successor to
the SCOPE carbon-cycle books of the 1970s and 1980s. It extends the work of the
IPCC in three main ways. First, it provides an update on key scientific discoveries in the
past few years. Second, it takes a comprehensive approach to the carbon cycle, treating
background and interactions with substantial detail. Managed aspects of the carbon
cycle (and aspects subject to potential future management) are discussed within the same
framework as the historical and current carbon cycle on the land, in the oceans, and in
the atmosphere. Third, this volume makes a real effort at synthesis, not only summar-
ing disciplinary perspectives, but also characterizing key interactions and uncertain-
ties between and at the frontiers of traditional disciplines.

This volume’s centerpiece is the concept that the carbon cycle, climate, and humans
work together as a single system (Figure 1.1). This systems-level approach focuses the sci-
ence on a number of issues that are almost certain to be important in the future and that,
in many cases, have not been studied in detail. Some of these issues concern the driving
forces of climate change and the ways that carbon-climate-human interactions modulate
the sensitivity of climate to greenhouse gas emissions. Others concern opportunities for
and constraints on managing greenhouse gas emissions and the carbon cycle.

The volume is a result of a rapid assessment project (RAP) orchestrated by SCOPE
(http://www.iscu-scope.org) and the Global Carbon Project (GCP, http://www.global-
carbonproject.org). Both are projects of the International Council for Science (ICSU,
http://www.icsu.org), the umbrella organization for the world’s professional scientific
societies. The GCP has additional sponsorship from the World Meteorological Orga-
nization (http://www.wmo.ch) and the Intergovernmental Oceanographic Commission
(http://ioc.unesco.org/iocweb/). The RAP process assembles a group of leading scien-
tists and challenges them to extend the frontiers of knowledge. The process includes
mutual education through a series of background papers and an intensive effort to
develop cross-disciplinary perspectives in a series of collectively written synthesis
papers. To provide timely synthesis on rapidly changing issues, the timeline is aggres-
Figure 1.1. (a) Schematic representation of the components of the coupled carbon-climate-human system and the links among them. Solid lines and (+) indicate positive feedbacks, feedbacks that tend to release carbon to the atmosphere and amplify climate change. Dashed lines and (-) indicate negative feedbacks, feedbacks that tend to sequester carbon and suppress climate change. GHG, in the center box, is greenhouse gases. ARD, in the lower right of the land box, is afforestation, reforestation, deforestation, the suite of forestry activities identified as relevant to carbon credits in the Kyoto Protocol. Over the next century, the oceans will continue to operate as a net carbon sink, but the land (in the absence of fossil emissions) may be either a source or sink. (b) Two complementary perspectives on human drivers of carbon emissions. In the Kaya identity widely used for economic analysis (left), emissions are seen as a product of four factors: population, per capita gross world product, the energy intensity of the gross world product, and the carbon intensity of energy production. From a political science perspective (right), the drivers emerge from interactions among policy, institutions, social organization, and knowledge and values.
The key messages from this assessment focus on five main themes that cut across all aspects of the carbon-climate-human system. The overarching theme of the book is that all parts of the carbon cycle are interrelated. Understanding will not be complete, and management will not be successful, in the absence of a framework that considers the full set of feedbacks, a set that almost always transcends both human actions and unmanaged systems. This systems perspective presents many challenges, because the interactions among very different components of the carbon cycle tend to be poorly recognized and understood. Still, the field must address these challenges. To do that, we must start with four specific themes that link the ideas discussed throughout the book. These four themes are (1) inertia and the consequence of entrained processes in the carbon, climate, and human systems, (2) unaccounted-for vulnerabilities, especially the prospects for large releases of carbon in a warming climate, (3) a series of gaps between reasonable expectations for future approaches to managing carbon and the requirements for stabilizing atmospheric CO₂, and (4) the need for a common framework for assessing natural and managed aspects of the carbon cycle. Each of these themes is previewed here and discussed extensively in the following chapters.

**Inertia**

Many aspects of the carbon-climate-human system change slowly, with a strong tendency to remain on established trajectories. As a consequence, serious problems may be
effectively entrained before they are generally recognized (Figure 1.2). Effective management may depend on early and consistent action, including actions with financial costs. The political will to support these costs will require the strongest possible evidence on the nature of the problems and the efficiency of the solutions.

The carbon-climate-human system includes processes that operate on a wide range of timescales, including many that extend over decades to centuries. The slow components have added tremendously to the challenge of quantifying human impacts on ocean carbon (Sabine et al., Chapter 2, this volume) and ocean heat content (Levitus et al. 2000). They also prevent the ocean from quickly absorbing large amounts of anthropogenic carbon (Sabine et al., Chapter 2) and underlie the very long lifetime of atmospheric CO$_2$.

Several new results highlight the critical role of inertia for the carbon cycle on land. It is increasingly clear that a substantial fraction of the current terrestrial sink, perhaps the majority, is a consequence of ecosystem recovery following past disturbances. Across much of the temperate Northern Hemisphere, changes in forestry practices, agriculture, and fire management have allowed forests to increase in biomass or area (Nabuurs, Chapter 16, this volume). Evidence that much of the recent sink on land is a result of land management has important implications for the future trajectory of the carbon cycle.
cycle. Beginning with Bacastow and Keeling (1973), most estimates of future carbon sinks have assumed that recent sinks were a consequence of CO₂ fertilization of plant growth and that past responses could be projected into the future with a CO₂-sensitivity coefficient or beta factor (Friedlingstein et al. 1995). To the extent that recent sinks are caused by management rather than CO₂ fertilization, past estimates of future sinks from CO₂ fertilization are likely to be too optimistic (Gruber et al., Chapter 3, this volume). Eventual saturation in sinks from management (Schimel et al. 2001) gives them a very different trajectory from that of sinks from CO₂ fertilization, especially those calculated by models without nutrient limitation (Prentice 2001).

In the human system, inertia plays a number of critical roles. The dynamics of development tend to concentrate future growth in carbon emissions in countries with developing economies (Romero Lankao, Chapter 19, this volume). This historical inertia, combined with potentially limited resources for carbon-efficient energy systems (Sathaye, Chapter 22), creates pressure for massive future emissions growth. Slowly changing institutions and incentive mechanisms in all countries (Lebel, Chapter 20) tend to entrain emissions trajectories further.

Inertia is profoundly important in the energy system, especially in the slow pace for introducing new technologies. The slow pace reflects not only the long time horizon for research and development, but also the long period required to retire existing capital stocks (Caldeira et al., Chapter 5). The long time horizon for bringing technologies to maturity and retiring capital stocks is only part of the timeline for the non-emitting energy system of the future, which also depends on the development of fundamentally new technologies (Hoffert et al. 2002). The search for fundamentally new energy sources cannot, however, constitute the entire strategy for action, because the entrained damage may be unacceptably large before new technologies are ready (Figure 1.2). A diverse portfolio of energy efficiency, new technologies, and carbon sequestration offers the strongest prospects for stabilizing atmospheric CO₂ (Caldeira et al., Chapter 5).

**Vulnerability**

A fundamental goal of the science of the carbon-climate-human system is to understand and eventually reduce the Earth’s vulnerability to dangerous changes in climate. This agenda requires that we understand the mechanisms that drive climate change, develop strategies for minimizing the magnitude of the climate change that does occur, and create approaches for coping with the climate change that cannot be avoided. Successful pursuit of this agenda is simpler when the carbon-climate-human system generates negative feedbacks (that tend to suppress further climate change), and it is more complicated when the system generates positive feedbacks (Figure 1.1). Positive feedbacks are especially challenging if they occur suddenly, as threshold phenomena, or if they involve coupled responses of the atmosphere, land, oceans, and human activities.

We are entering an era when we need not—and in fact must not—view the ques-
tion of vulnerability from any single perspective. The carbon-climate-human system generates climate change as an integrated system. Attempts to understand the integrated system must take an integrated perspective. Mechanistic process models, the principal tools for exploring the behavior of climate and the carbon cycle on land and in the oceans, are increasingly competent to address questions about interactions among major components of the system (Gruber et al., Chapter 3, this volume). Still, many of the key interactions are only beginning to appear in models or are not yet represented. For these interactions, we need a combination of dedicated research and other tools for taking advantage of the available knowledge. In assessing the vulnerability of the carbon cycle to the possibility of large releases in the future, we combine results from mechanistic simulations with a broad range of other kinds of information.

Several new lines of information suggest that past assessments have underestimated the vulnerability of key aspects of the carbon-climate-human system. Several of these concern climate-carbon feedbacks. Simulations with coupled climate-carbon models demonstrate a previously undocumented positive feedback between warming and the terrestrial carbon cycle, in which CO₂ releases stimulated by warming accelerate warming and further CO₂ releases (Friedlingstein, Chapter 10, this volume). The experiments to date are too limited to support an accurate quantification of this positive feedback, but the range of results highlights the importance of further research. The behavior of two models of comparable sophistication is so different that, with similar forcing, they differ in atmospheric CO₂ in 2100 by more than 200 parts per million (ppm).

The models that simulate the future carbon balance of land are still incomplete. At least three mechanisms either not yet represented or represented in the models in a rudimentary way have the potential to amplify positive feedbacks to climate warming (Gruber et al., Chapter 3). The first of these is the respiration of carbon currently locked in permanently frozen soils. General Circulation Model (GCM) simulations indicate that much of the permafrost in the Northern Hemisphere may disappear over the next century. Because these soils contain large quantities of carbon (Michaelson et al. 1996), and because much of this carbon is relatively labile once thawed, potential releases over a century could be in the range of 100 PgC (Gruber et al., Chapter 3). Wetland soils are similar, containing vast quantities of carbon, which is subject to rapid decomposition when dry and aerated. Drying can allow wildfires, such as those that released an estimated additional 0.8 to 3.7 PgC from tropical fires during the 1997–1998 El Niño (Langenfelds et al. 2002). Drying wetland soils might result in a decrease in methane emissions, along with an increase in CO₂ emissions, requiring a careful analysis of overall greenhouse forcing (Manne and Richels, Chapter 25). A third aspect of the terrestrial biosphere with the potential for massive carbon releases in the future is large-scale wildfire, especially in tropical and boreal forest ecosystems (Gruber et al., Chapter 3). Climate changes in both kinds of ecosystems could push large areas past a threshold where they are dry enough to support large wildfires (Nepstad et al. 2001), and a fundamental change in the fire regime could effectively eliminate large areas of forest. None
of these three mechanisms is thoroughly addressed in current ecosystem or carbon-cycle models. As a consequence, it is not yet feasible to estimate either the probability of the changes or the likely carbon emissions. Still, ignoring the potential for these large releases is not responsible, and the vulnerability of the climate system to them should be explored.

Vulnerability of ecosystems used for carbon management highlights other aspects of the need for an integrated perspective on the carbon-climate-human system. Ocean fertilization and deep disposal both create altered conditions for ocean ecosystems (Bakker, Chapter 26; Brewer, Chapter 27). To date, the consequences of these alterations are poorly known. Ecosystem alteration is also an issue for terrestrial sequestration through afforestation. Especially where afforestation involves plantations of a single tree species or non-native species, it is important to assess how any extra vulnerability to loss of ecosystem services alters the overall balance of costs and benefits (Raupach et al., Chapter 6, this volume).

The Energy Gap

Humans interact with nearly every aspect of the carbon cycle. In the past, trajectories of emissions and land use change unfolded with little or no reference to their impacts on climate. Now much of the world is ready to make carbon management a priority. The United Nations Framework Convention on Climate Change and its Kyoto Protocol establish initial steps toward stabilizing the climate (Sanz et al., Chapter 24, this volume). In the future, however, much more will need to be done, especially if CO₂ concentrations are to be stabilized at a concentration of 750 ppm or lower. The basic problem is that world energy demand continues to grow rapidly. With a business-as-usual strategy, global carbon emissions could exceed 20 PgC per year (y⁻¹) (about three times current levels) by 2050 (Nakicenovic, Chapter 11).

Many technologies present options for decreasing emissions or sequestering carbon. Unfortunately, no single technology appears to have the potential to solve the energy problem comprehensively within the next few decades (Caldeira et al., Chapter 5, this volume). Indeed, meeting world energy demands without carbon emissions may require fundamental breakthroughs in energy technology (Hoffert et al. 2002). Even with future breakthroughs, the best options for managing the future energy system are very likely to involve a portfolio of approaches, including strategies for extracting extra energy from carbon-based fuels, technologies for generating energy without carbon emissions, and approaches to increasing sequestration on the land and in the oceans (Caldeira et al., Chapter 5).

Increases in energy efficiency (measured as energy per unit of carbon emissions) typically accompany economic development, and it is reasonable to assume that efficiency increases will continue in the future (Sathaye, Chapter 22). Even with aggressive assumptions about increases in efficiency, reasonable scenarios for the future may result
in CO₂ levels well above widely discussed stabilization targets (i.e., 450, 550, and 750 ppm CO₂). This is the case for many of the scenarios explored in the IPCC Special Report on Emission Scenarios (Nakicenovic, Chapter 11), leading to a gap between emissions consistent with reasonable advances in energy technology and those required to reach a particular stabilization target. This gap needs to be filled through active policies and could include incentives for new technologies, sequestration, or decreased energy consumption (Edmonds et al., Chapter 4).

The juxtaposition of the portfolio of future options for energy and carbon management with the gap between many economic scenarios and CO₂ stabilization creates a problem. A priori, it is not possible to identify a set of options available for filling the energy gap because most or even all of the available options may have already been used in the increased energy efficiency that occurs as a natural part of technological advance (Figure 1.3). Because there is no way to predict the mechanisms that will appear endogenously, there is no simple way to identify an additional set that should be the targets for policy intervention. From a carbon management perspective, the efficiency

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**Figure 1.3.** The energy gap, showing the growing difference between the emissions projected in a widely used scenario (IS92a) and the emissions required to stabilize atmospheric CO₂ at 550 ppm (with the WRE 550 scenario [Edmonds et al., Chapter 4, this volume]). This energy gap is the target for climate policy. Also shown is the emissions trajectory for IS92a in the absence of endogenous technology improvements. The very large improvements can be expected based on past experience, but they may involve many of the options that are also candidates for closing the energy gap between the emissions scenario (IS92a) and the stabilization scenario (550 ppm constraint). Redrawn from Edmonds et al., Chapter 4.
increases that occur spontaneously make some aspects of the carbon problem simpler, and they make some aspects more difficult to solve. On the one hand, if economic pressures consistently lead to efficiency increases, additional policy tools may not be necessary, at least for some of the efficiency increases. On the other hand, if the efficiency increases in the economic scenarios consume most of the options for carbon management, the costs of developing options for closing the gap may be very high (Edmonds et al., Chapter 4) or they may entail unacceptable trade-offs with other sectors (Raupach et al., Chapter 6).

**Toward a Common Framework**

Some of the greatest challenges in managing the carbon-climate-human system for a sustainable future involve establishing appropriate criteria for comparing options. Ultimately, we need a framework where any option can be explored in terms of its implications for the climate system, its implications for energy, and its other impacts on ecosystems and humans (Raupach et al., Chapter 6). Many of the challenges involve processes that operate on different timescales. The sensitivity to time frame of the relative value of mitigating CO₂ and CH₄ emissions illustrates the problem. On a timescale of a few years, decreasing CH₄ emissions has a large impact on climate, but this impact decreases over decades as a consequence of the relatively short atmospheric life of CH₄ (Manne and Richels, Chapter 25). Carbon management through reforestation and afforestation potentially yields benefits over many decades, but these benefits disappear or reverse when forests stop growing, are harvested, or are disturbed. A decision about using a plot for a forest plantation versus a photovoltaic array needs to be based on a common framework for assessing the options, a framework that includes not only time frames, but also ancillary costs and benefits (Edmonds, Chapter 23).

All of the decisions that underlie the transition to a sustainable energy future require placing the decision in a larger context (Raupach et al., Chapter 6). Institutions, culture, economic resources, and perspectives on intergenerational equity all shape opportunities for and constraints on managing the carbon cycle.

**Meeting Future Challenges**

Each of the themes that emerged from the RAP on the carbon cycle tends to make the climate problem more difficult to solve. The role of land management in current sinks suggests that future sinks from CO₂ fertilization will be smaller than past estimates. Inertia in the human system extends the timeline for developing and implementing solutions. Land ecosystems appear to be vulnerable to large releases of carbon, including releases from several mechanisms that have been absent from or incomplete in the models used for past assessments. Strategies for increased energy efficiency, carbon sequestration, and carbon-free energy are abundant, but no single technology is likely
to solve the climate problem completely in the next few decades. A portfolio approach is the best option, but many of the elements of the portfolio are implicitly present in economic scenarios that fail to meet stabilization targets. Finally, each of the strategies for increased energy efficiency, carbon sequestration, or carbon-free energy involves a series of ancillary costs and benefits. In the broad context of societal issues, the ancillary effects may dominate the discussion of implementation.

How should an appreciation of the new dimensions of the climate problem change strategies for finding and implementing solutions? The most obvious conclusion is that the problem of climate change warrants more attention and higher priority. It also warrants a broader discussion of strategies, a discussion that should move beyond land, atmosphere, oceans, technology, and economics to include serious consideration of equity, consumption, and population.

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