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In 2004, Island Press celebrates its twentieth anniversary as the leading provider of timely and practical books that take a multidisciplinary approach to critical environmental concerns. Our growing list of titles reflects our commitment to bringing the best of an expanding body of literature to the environmental community throughout North America and the world.

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The opinions expressed in this book are those of the author(s) and do not necessarily reflect the views of these foundations.

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.

SCOPE 62

The Global Carbon Cycle

The Scientific Committee on Problems of the Environment (SCOPE)

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SCOPE 62: *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World,* edited by Christopher B. Field and Michael R. Raupach

SCOPE 62

The Global Carbon Cycle

Integrating Humans, Climate, and the Natural World

Edited by
Christopher B. Field
and Michael R. Raupach

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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 intelligence 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, policy 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 carbon cycle in general. Initial attempts, through the United Nations Framework Convention 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 scientific 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 very able Scientific Steering Committee for the rapid assessment project (RAP) on the carbon cycle included Niki Gruber, Jingyun Fan, Inez Fung, Jerry Melillo, Rich Richels, Chris Sabine, Riccardo Valentini, and Reynaldo Victoria. Reynaldo was a superb local host, spreading the resources of Brazil before the meeting participants. The laboratory Reynaldo directs, the Centro de Energia Nuclear na Agricultura (CENA), provided a wealth of institutional support, including able assistance from Daniel Victoria, Vicki Balasteras, and Alex. Technical support from the Inter-American Institute (IAI) was invaluable, with Luis Marcelo Achite and Marcella Ohira Schwarz helping to keep the meeting on track. Without Luiz Martinelli's contributions as beach patrol agent, the meeting's sessions would have never reached a quorum. Jan Brown was a dedicated and efficient volunteer editor. The SCOPE editorial team, John Stewart (editor in chief) and Susan Greenwood Etienne (managing editor for the RAP series), crafted a smooth transition from meeting mode to book mode. The Island Press editorial team, including Todd Baldwin, James Nuzum, David Peattie, and Heidi Fritschel, was efficient and professional. Veronique Plocq-Fichelet, the executive director of SCOPE, and Pep Canadell, the project officer for the Global Carbon Project, both opened many doors by making this RAP a priority.

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.

Chris Field
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October 2003

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

Christopher B. Field, Michael R. Raupach, and Reynaldo Victoria

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 CO_2 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 CO_2 (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. 1979), 1981 (Bolin 1981), and 1989 (Bolin et al. 1989).

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 scientific 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 participation 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 summarizing disciplinary perspectives, but also characterizing key interactions and uncertainties 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 science 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.icsu-scope.org) and the Global Carbon Project (GCP, http://www.globalcarbonproject.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 Organization (http://www.wmo.ch) and the Intergovernmental Oceanographic Commission (http://ioc.unesco.org/iocweb/). The RAP process assembles a group of leading scientists 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-

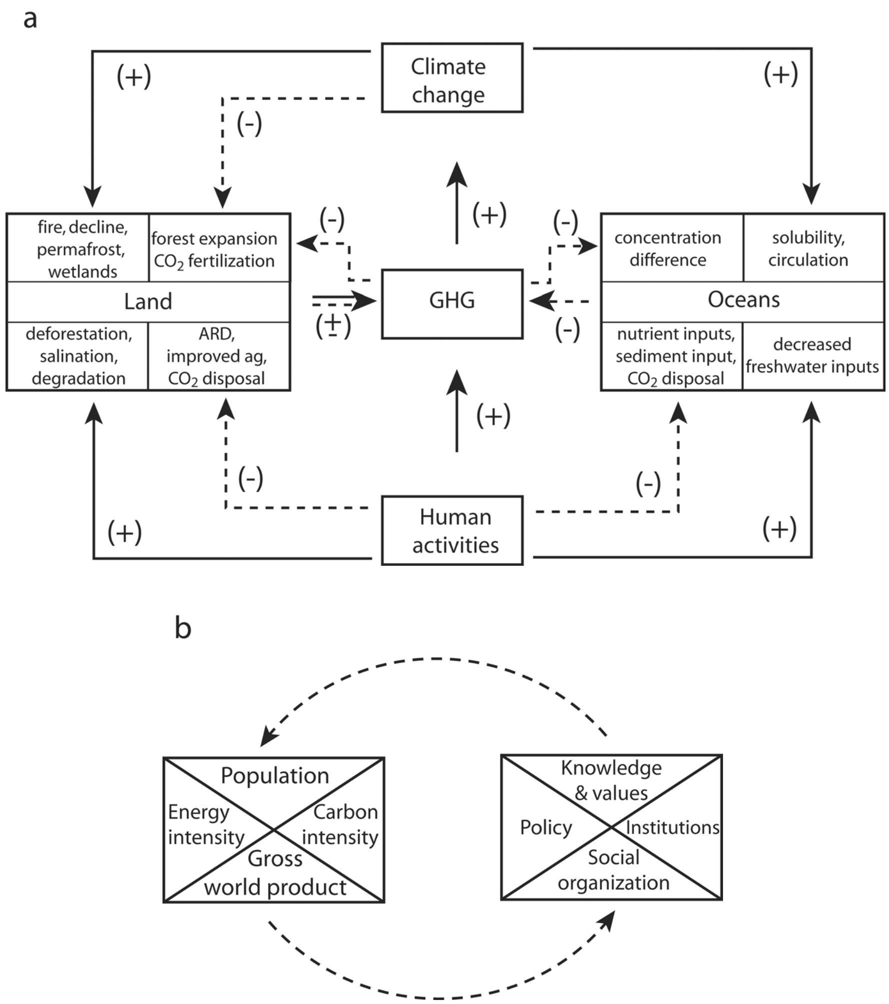

Figure 1.1. (a) Schematic representation of the components of the coupled carbon-climate-human system and the links among them. Solid lines and (+) indicate positive feedbacks, feedbacks that tend to release carbon to the atmosphere and amplify climate change. Dashed lines and (-) indicate negative feedbacks, 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.

sive. All of the authors worked with the editors and the publisher to produce a finished book within nine months of the synthesis meeting.

The book is organized into seven parts. Part 1 contains the crosscutting chapters, which address the current status of the carbon cycle (Sabine et al., Chapter 2), the future carbon cycle of the oceans and land (Gruber et al., Chapter 3), possible trajectories of carbon emissions from human actions (Edmonds et al., Chapter 4), approaches to reducing emissions or sequestering additional carbon (Caldeira et al., Chapter 5), and the integration of carbon management in the broader framework of human and Earth-system activities (Raupach et al., Chapter 6). Part 2 provides an overview of the carbon cycle, with chapters on historical patterns (Joos and Prentice, Chapter 7), recent spatial and temporal patterns (Heimann et al., Chapter 8), greenhouse gases other than CO_2 (Prinn, Chapter 9), two-way interactions between the climate and the carbon cycle (Friedlingstein, Chapter 10), and the socioeconomic trends that drive carbon emissions (Nakicenovic, Chapter 11). Parts 3 through 7 provide background and a summary of recent findings on the carbon cycle of the oceans (Le Quéré and Metzl, Chapter 12; Greenblatt and Sarmiento, Chapter 13), the land (Foley and Ramankutty, Chapter 14; Baldocchi and Valentini, Chapter 15; Nabuurs, Chapter 16), land-ocean margins (Richey, Chapter 17; Chen, Chapter 18), humans and the carbon cycle (Romero Lankao, Chapter 19; Lebel, Chapter 20; Tschirley and Servin, Chapter 21), and purposeful carbon management (Sathaye, Chapter 22; Edmonds, Chapter 23; Sanz et al., Chapter 24; Manne and Richels, Chapter 25; Bakker, Chapter 26; Brewer, Chapter 27; Smith, Chapter 28; and Robertson, Chapter 29).

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 CO_2, 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

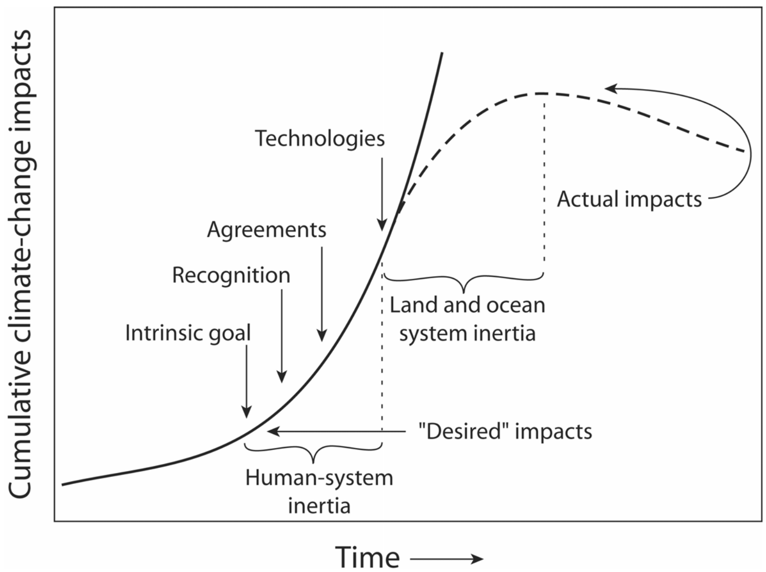

Figure 1.2. Effects of inertia in the coupled carbon-climate-human system. If there are delays associated with (1) assembling the evidence that climate has moved outside an acceptable envelope, (2) negotiating agreements on strategy and participation, and (3) developing new technologies to accomplish the strategies, then there will be additional delays associated with internal dynamics of the land and ocean system. As a consequence, the actual climate change may be far greater than that originally identified as acceptable.

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. Beginning with Bacastow and Keeling (1973), most estimates of future carbon sinks have assumed that recent sinks were a consequence of CO_2 fertilization of plant growth and that past responses could be projected into the future with a CO_2-sensitivity coefficient or beta factor (Friedlingstein et al. 1995). To the extent that recent sinks are caused by management rather than CO_2 fertilization, past estimates of future sinks from CO_2 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 CO_2 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 CO_2 (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 question 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 CO_2 releases stimulated by warming accelerate warming and further CO_2 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 CO_2 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 CO_2 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 CO_2 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

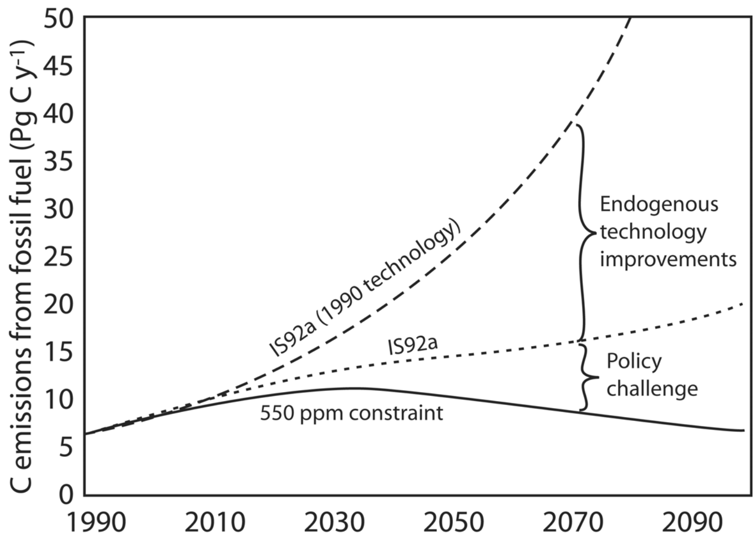

Figure 1.3. The energy gap, showing the growing difference between the emissions projected in a widely used scenario (IS92a) and the emissions required to stabilize atmospheric CO_2 at 550 ppm (with the WRE 550 scenario [Edmonds et al., Chapter 4, this volume]). This energy gap is the target for climate 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.

in CO_2 levels well above widely discussed stabilization targets (i.e., 450, 550, and 750 ppm CO_2). 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 CO_2 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 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 CO_2 and CH_4 emissions illustrates the problem. On a timescale of a few years, decreasing CH_4 emissions has a large impact on climate, but this impact decreases over decades as a consequence of the relatively short atmospheric life of CH_4 (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 CO_2 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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