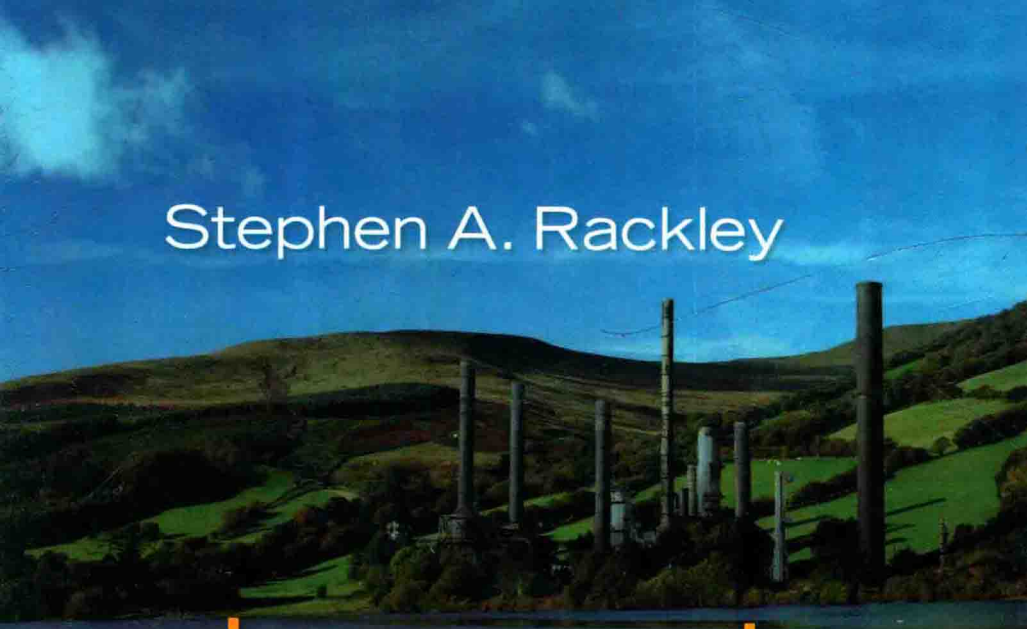
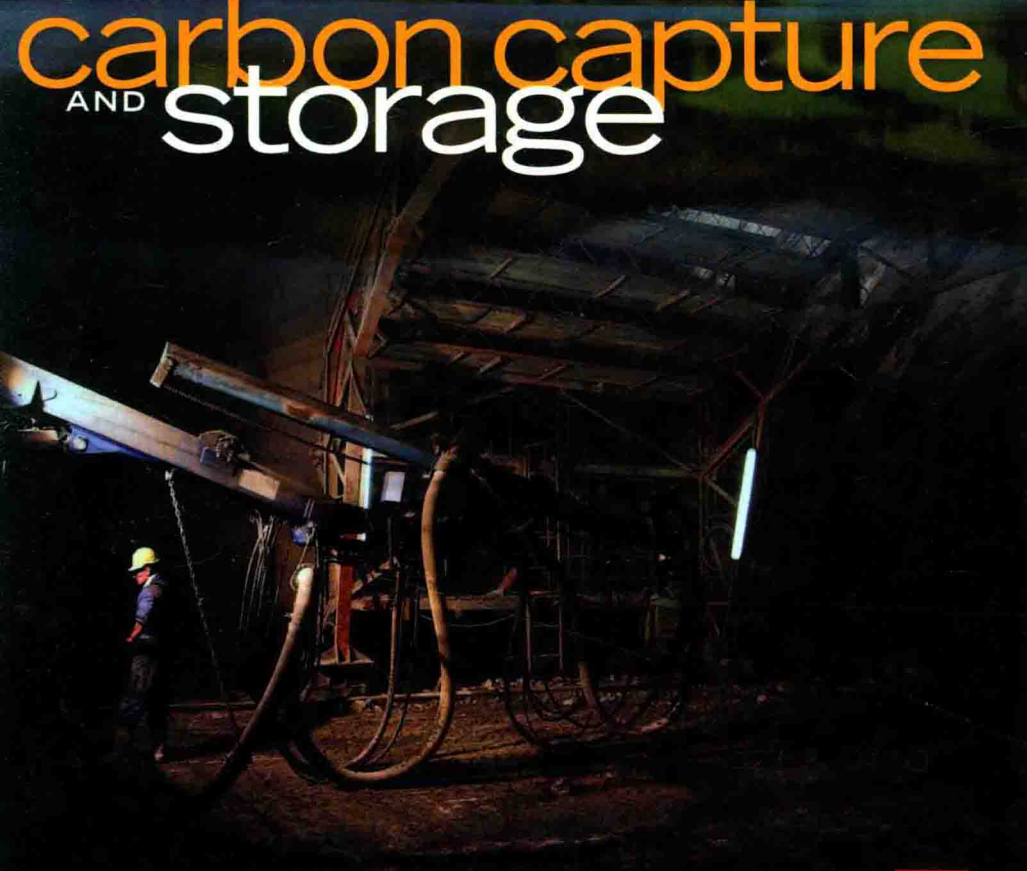
Stephen A. Rackley



carbon capture AND storage



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Carbon Capture and Storage

Stephen A. Rackley

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for
Adam and Jenny
and their
children's children's
children

Preface

The seed from which this book has grown was planted by the launch of the Virgin Earth Challenge by Sir Richard Branson and former U.S. Vice President Al Gore on Feb. 9, 2007. The aim of the Challenge is to encourage the development of commercially viable new technology, processes, and methods that can remove significant volumes of anthropogenic greenhouse gases from the atmosphere and contribute materially to the stability of the earth's climate.

With emissions from fossil fuel combustion running at 6.0–6.5 Gt-C per year (Gt-C = 10^9 metric tonnes of carbon), a material contribution to climate stability implies the potential for deployment on a scale of 1 Gt-C per year, roughly a thousand times larger than any currently operating project. While these volumes seem prodigious, anthropogenic emissions pale into insignificance beside the natural fluxes such as terrestrial photosynthesis, at ~120 Gt-C year, and oceanic uptake and release at ~90 Gt-C per year.

A diverse range of carbon capture and storage (CCS) technologies are currently at various stages of research, development, and demonstration. While a few of these technologies have reached the deployment stage, many still require significant further development work to improve technical capabilities and reduce costs. Although front-runners are already emerging, it is likely that the long-term potential of CCS will be achieved through the application of a broad portfolio of different technologies. These could range from the current favorite—solvent-based capture from coal-fired power plants with geological storage—to the decarbonation of fuels ahead of combustion, the manipulation of ecological factors such as microbial populations or ocean fertility to increase carbon inventories in soils and in the oceans, and many others.

The aim of this book is to contribute in small part to the progress of this endeavor by providing a comprehensive, technical, but nonspecialist overview of technologies at various stages of maturity that, it is hoped, will provide technical background for decision makers and encourage a coming generation of students and young engineers to tackle the 21st century's most important technological challenge.

The book is presented in five parts, dealing in turn with fundamentals, capture, storage and monitoring, transportation, and information resources.

The three chapters of Part I establish some fundamentals. Chapter 1 describes the global carbon cycle and outlines the perturbing impact of anthropogenic carbon dioxide emissions on carbon fluxes and sinks. In Chapter 2, a brief initial overview of CCS technologies is given, taking each of the main industrial sources of carbon emissions as the starting point. Since capture from

power generation plants will be a major focus of early CCS implementation, Chapter 3 provides a fairly comprehensive introduction to power generation technologies. The emphasis here is on the current state of the art and on systems under development that are likely to be deployed during the period in which CCS technologies mature.

With these foundations established, Part II provides a more detailed description of carbon capture technologies. The first two chapters are written from an industry perspective, for the power industry (Chapter 4) and other industries (Chapter 5), and the next five chapters from a technology perspective, covering absorption, adsorption, membrane, cryogenic, and mineral carbonation technologies.

Part III then addresses the storage of captured CO_2 and related monitoring requirements, covering geological storage (Chapter 11), ocean storage (Chapter 12), and storage in terrestrial ecosystems (Chapter 13). The final chapter in Part III describes opportunities to increase industrial usage of CO_2 in ways that can significantly contribute to global CCS objectives, such as low-carbon cement and biofuel production.

The transportation of CO_2 between capture and storage sites, either by pipeline infrastructure or by marine transport, is covered in Part IV.

The book concludes in Part V with a compendium of information resources, including units and conversion factors, a list of key abbreviations, and a glossary of some of the key technical terms encountered.

While the focus of this book is on the technical aspects of CCS, many other factors will play a part in determining the extent to which CCS technologies are eventually deployed—chief among them being costs. Apart from some general indications of currently estimated or target costs of some CCS options, this book avoids any analysis of the cost of implementation of the various technologies discussed. The capital and operating costs and the economics of individual CCS projects will be highly case-dependent, with exchange rate volatility further complicating any general analysis. Future reductions in the costs and energy requirements of CCS technologies can also be expected, pending the outcome of further R&D efforts and the learning from early demonstration projects. The extent and timing of these improvements and their impact on overall capture costs are highly uncertain, so that current costs are a poor guide to either actual or relative future CCS implementation prospects or costs.

Various chapters of the book have benefited from review by a number of scientists and other professionals who are engaged in the broad range of technologies described here. My special thanks are due to Dr. John Benemann (Benemann Associates), Dr. Somayeh Goodarzi (University of Calgary), Rob and Karin Lavoie (Calpetra Research & Consulting), Dr. Klaus Lorenz (Ohio State University), Dr. Antonie Oosterkamp (Research Foundation Polytec), Dr. Edward Peltzer (Monterey Bay Aquarium Research Institute), Prof. James Ritter (University of South Carolina), Prof. Anja Schuster (Universität Stuttgart), Dr. Takahisa Yokoyaka (Central Research Institute of Electric Power Industry [CRIEPI]), and Prof. Ron Zevenhoven (Åbo Akademi University).

Their critical input, generously provided, is reflected in these pages; the responsibility for the remaining shortcomings, errors, and omissions remains with the author. Any comments, suggestions, or other feedback from readers will be most welcome; please send them to ccst2010@gmail.com.

It has been a pleasure to work with the team at Elsevier in bringing this book to fruition, and my thanks are due to Ken McCombs and Irene Hosey, who shepherded and supported it from concept to completion, and to the production team—notably Donald Whitehead of MPS Content Services and Anne McGee—ably led by Maria Alonso.

A final word of thanks is due to Serge, Brin, and Jimmy, without whose vision this project would have been a far greater challenge.

In the two decades since the 1990 publication by the UN Intergovernmental Panel on Climate Change of its First Assessment Report, in the face of an increasing body of evidence and understanding, the Panel's careful language of uncertainty has been progressively strengthened to the point where the Fourth Assessment Report was able to state with very high confidence that "the net effect of human activities since 1750 has been one of warming. Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations" (IPCC AR4, 2007).

Looking beyond AR5, due in 2014, with new evidence mounting daily that the climatic impact of our activities is at the upper end of the range of predictions, the task before us is to ensure that, at the end of our finite window of opportunity for change, we do not conclude ...

"This earth is ruined! We gotta get a new one." (Fey, T. (2007). Greenzo, *30Rock*, **2** (5)).

Stephen A. Rackley
August 2009

Acknowledgements

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Contents

Part I

Introduction and overview

1 Introduction

The fossil fuel resources of our planet—estimated at between 4000 and 6000 gigatonnes of carbon (Gt-C)—are the product of biological and geologic processes that have occurred over hundreds of million of years and continue today. The carbon sequestered in these resources over geological time was originally a constituent of the atmosphere of a younger earth—an atmosphere that contained ~1500 parts per million (ppm) CO_2 at the beginning of the Carboniferous age, 360 million years ago, when the evolution of earth's first primitive forests began the slow process of biogeological sequestration.

Since the dawn of the industrial age, circa 1750, and particularly since the invention of the internal combustion engine, ~5% of these resource volumes have been combusted and an estimated 280 Gt-C released back into the atmosphere in the form of CO_2. In the same period a further ~150 Gt-C has been released to the atmosphere from soil carbon pools as a result of changes in land use. The atmospheric, terrestrial, and oceanic carbon cycles have dispersed the greater part of these anthropogenic emissions, locking the CO_2 away by dissolution in the oceans and in long-lived carbon pools in soils. During the period since 1750, the CO_2 concentration in the atmosphere has increased from 280 ppm to 368 ppm in 2000, and ~388 ppm in 2010, the highest level in the past 650,000 years and one that is not likely to have been exceeded in the past 20 million years, where "likely" reflects the Intergovernmental Panel on Climate Change (IPCC) judgment of a 66–90% chance.

This increase in atmospheric CO_2 concentration ($[CO_2]$) influences the balance of incoming and outgoing energy in the earth-atmosphere system, CO_2 being the most significant anthropogenic greenhouse gas (GHG). In its Fourth Assessment Report (AR4), published in 2007, the IPCC concluded that global average surface temperatures had increased by 0.74 ± 0.18°C over the 20th century (Figure 1.1), and that "most of the observed increase in global average temperatures since the mid-20th century is very likely (*>90% probability*) due to the observed increase in anthropogenic GHG concentrations."

Although anthropogenic CO_2 emissions are relatively small compared to the natural carbon fluxes—for example, photosynthetic and soil respiration fluxes, at ~60 Gt-C per year, are 10 times greater than current emissions from fossil fuel combustion—these anthropogenic releases have occurred on a time scale of hundreds rather than hundreds of millions of years. Anthropogenic change has also reduced the effectiveness of certain climate feedback mechanisms; for

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example, changes in land-use and land-management practices have reduced the ability of soils to build soil carbon inventory in response to higher atmospheric CO_2, while ocean acidification has reduced the capacity of the oceans to take up additional CO_2 from the atmosphere.

The energy consumption of modern economies continues to grow, with some scenarios predicting a doubling of global energy demand between 2010 and 2050. Fossil fuels currently satisfy 85% of global energy demand and fuel a similar proportion of global electricity generation, and their predominance in the global energy mix will continue well into the 21st century, perhaps much longer. In the absence of mitigation, the resulting emissions will lead to further increase in atmospheric $[CO_2]$, causing further warming and inducing many changes in global climate. Even if $[CO_2]$ is stabilized before 2100, the warming and other climate effects are expected to continue for centuries, due to the long time scales associated with climate processes. Climate predictions for a variety of stabilization scenarios suggest warming over a multicentury time scale in the range of 2°C to 9°C, with more recent results favoring the upper half of this range.

Although many uncertainties remain, there is little room for serious doubt that measures to reduce CO_2 emissions are urgently required to minimize long-term climate change. While research and development efforts into low- or zero-carbon alternatives to the use of fossil fuels continues, the urgent need to move toward stabilization of $[CO_2]$ means that measures such as the capture and storage of carbon that would otherwise be emitted can play an important role during the period of transition to low-carbon alternatives.

Within the field of carbon capture and storage (CCS), a diverse range of technologies is currently under research and development and a growing number of demonstration projects have been started or are planned. A few technologies have already reached the deployment stage, where local conditions or project specifics have made them economically viable, but for most technologies further development work is required to improve technical capabilities and reduce costs.

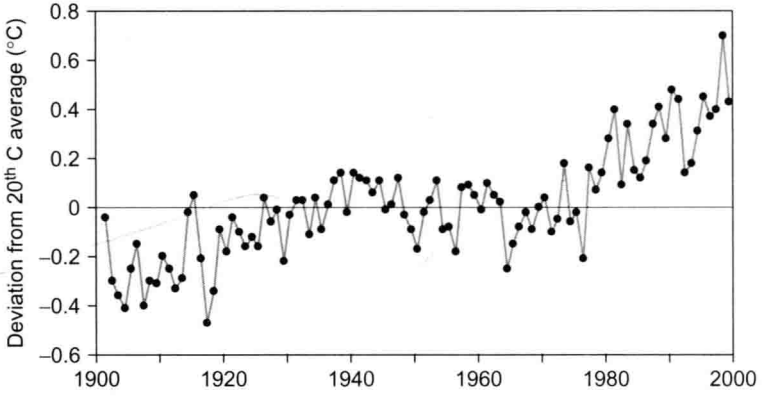

Figure 1.1 Variation of the earth's surface temperature during the 20th century (IPCC data)

Although it is possible with some confidence to identify the technologies that are most likely to yield to these efforts, it is also likely that the full long-term potential of CCS for emissions reduction will be achieved through the application of a broad portfolio of different technical solutions.

The remainder of this chapter provides the context for this challenge. Firstly, the inventories and fluxes that make up the global carbon cycle are discussed. While the current CCS frontrunners make a direct attack on anthropogenic emissions by capturing CO_2 from large sources before emission, reduction of the atmospheric carbon inventory can be achieved by any approach that can limit fluxes contributing to or enhance fluxes reducing this inventory. An understanding of these inventories and fluxes is therefore an essential grounding.

Finally, the process of technological innovation is described. The concepts and terminology introduced here will be used throughout the book to locate various technologies and projects within the life cycle of technology development from research to commercial deployment.

1.1 The carbon cycle

The carbon inventories in the atmosphere, biosphere, soils and rocks, and the oceans are linked by a complex set of natural and anthropogenic biogeochemical processes that are collectively known as the carbon cycle. Figure 1.2 illustrates the inventories (bold font, units of Gt-C) and fluxes (italic font, units of Gt-C per year) that make up this cycle.

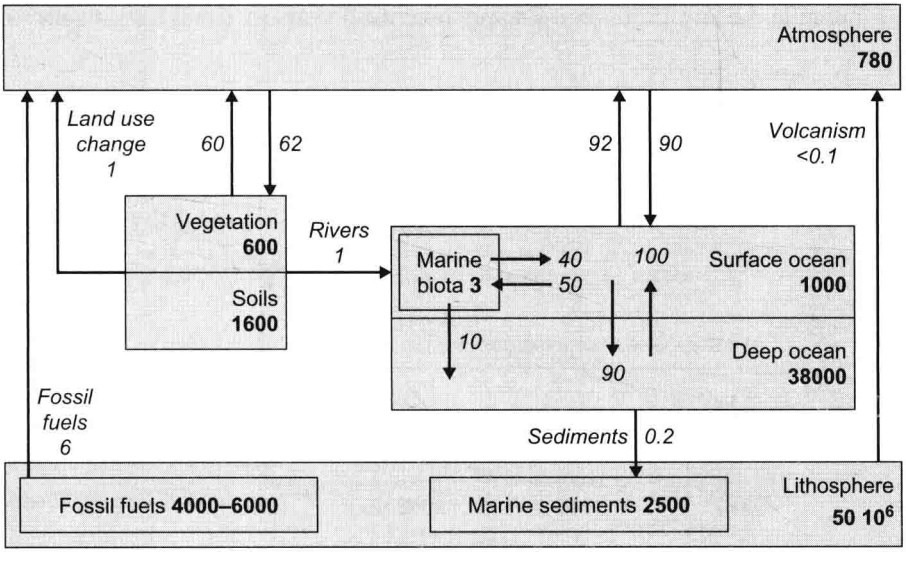

Figure 1.2 Inventories and fluxes in the carbon cycle (2008 estimates)

1.1.1 Carbon inventories

The main inventories relevant to the global carbon cycle are described in the following section.

Carbon inventory of the atmosphere

The atmospheric carbon inventory consists almost entirely of carbon dioxide, with a concentration [CO_2] of some 388 ppm (2010) or 0.04% by volume. As noted above, this inventory has risen by almost 40% since preindustrial times as a net result of emissions from fossil fuel combustion and changes in land-use and land-management practices. The remaining atmospheric carbon inventory consists of methane (CH_4) at ~1.8 ppm, with traces of carbon monoxide (CO) and anthropogenic chlorofluorocarbons (CFCs) also present.

Detailed measurements of [CO_2] were started by Charles Keeling at the National Oceanic and Atmospheric Administration (NOAA) Mauna Loa Observatory, Hawaii, in September 1957, establishing an average value of 315 ppm for the first full year of measurements. The curve of increasing [CO_2] established since that time is known as the Keeling curve, and the past two decades of data from Mauna Loa are shown in Figure 1.3.

The cyclical overprint on the continuously rising trend is shown in Figure 1.4 for each individual year from 2000 to 2008 and as an average over this period. The cycle is synchronized with the Northern Hemisphere seasons, where [CO_2] is drawn down ~3.5 ppm below the annual average trend by photosynthetic production from May to September and rebounds by a similar amount as a result of biomass decomposition from October to April.

The amplitude of this annual [CO_2] cycle at Mauna Loa has increased from ~5.7 ppm in the late 1950s to ~6.4 ppm over the 5 years to 2008. This is believed

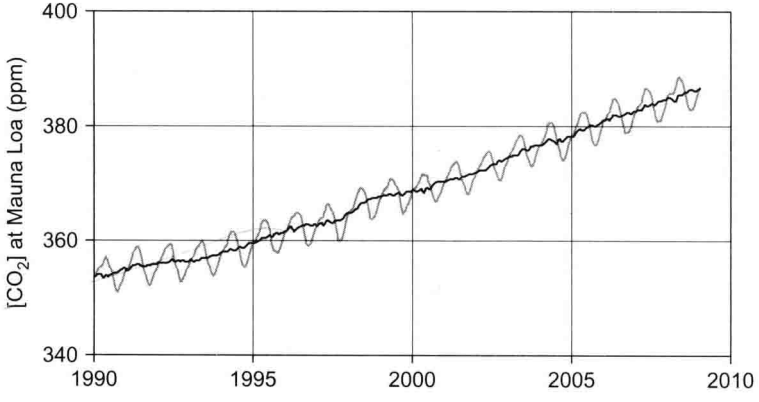

Figure 1.3 [CO_2] at Mauna Loa Observatory (Data courtesy NOAA, Earth System Research Laboratory, Global Monitoring Division)