



Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration

DETAILS

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Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts; Board on Atmospheric Sciences and Climate; Ocean Studies Board; Division on Earth and Life Studies; National Research Council

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CLIMATE INTERVENTION

Carbon Dioxide Removal and Reliable Sequestration

Committee on Geoengineering Climate:
Technical Evaluation and Discussion of Impacts

Board on Atmospheric Sciences and Climate

Ocean Studies Board

Division on Earth and Life Studies

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Preface

The signs of a warming planet are all around us: rising seas, melting ice sheets, record-setting temperatures, with impacts cascading to ecosystems, humans, and our economy. At the root of the problem, anthropogenic greenhouse gas emissions to the atmosphere continue to increase, a substantial fraction of which diffuse into the ocean, causing ocean acidification and threatening marine ecosystems. Global climate is changing faster than at any time since the rise of human civilization, challenging society to adapt to those changes. If the current dependence on fossil fuel use continues, evidence from previous periods of high atmospheric greenhouse gas concentrations indicates that our release of fossil fuel carbon into Earth's atmosphere in the form of CO₂ will be recorded in the rock record as a major planet-wide event, marked by transgressions of shorelines, extinctions of biota, and perturbations of major biogeochemical cycles.

The specific topic of this report, "climate geoengineering," was often framed in terms of a last-ditch response option to climate change if climate change damage should produce extreme hardship. Such deliberate intervention in the climate system was often considered a taboo subject. Although the likelihood of eventually considering last-ditch efforts to address damage from climate change grows with every year of inaction on emissions control, there remains a lack of information on these ways of potentially intervening in the climate system. In 2012 the U.S. government, including several of the science agencies, asked the National Academy of Sciences to provide advice on this subject. The National Research Council (NRC) committee assembled in response to this request realized that carbon dioxide removal and albedo modification (i.e., modification of the fraction of short-wavelength solar radiation reflected from Earth back into space) have traditionally been lumped together under the term "geoengineering" but are sufficiently different that they deserved to be discussed in separate volumes.

Carbon dioxide removal strategies, discussed in the first volume, are generally of lower risk and of almost certain benefit given what is currently known of likely global emissions trajectories and the climate change future. Currently, cost and lack of technical maturity are factors limiting the deployment of carbon dioxide removal strategies for helping to reduce atmospheric CO₂ levels. In the future, such strategies could, however, contribute as part of a portfolio of responses for mitigating climate warming and ocean acidification. In the meantime, natural air CO₂ removal processes (sinks) con-

PREFACE

sume the equivalent of over half of our emissions, a feature that might be safely and cost-effectively enhanced or augmented as explored in the first volume.

In contrast, albedo modification approaches show some evidence of being effective at temporarily cooling the planet, but at a currently unknown environmental price. The committee is concerned that understanding of the ethical, political, and environmental consequences of an albedo modification action is relatively less advanced than the technical capacity to execute it. In fact, one serious concern is that such an action could be unilaterally undertaken by a nation or smaller entity for their own benefit without international sanction and regardless of international consequences. A research basis is currently lacking to understand more about the potential results and impacts of albedo modification to help inform such decisions. These approaches are discussed in the second volume.

The committee's very different posture concerning the currently known risks of carbon dioxide removal as compared with albedo modification was a primary motivation for separating these climate engineering topics into two separate volumes.

Terminology is very important in discussing these topics. "Geoengineering" is associated with a broad range of activities beyond climate (e.g., geological engineering), and even "climate engineering" implies a greater level of precision and control than might be possible. The committee concluded that "climate intervention," with its connotation of "an action intended to improve a situation," most accurately describes the strategies covered in these two volumes. Further, the committee chose to avoid the commonly used term of "solar radiation management" in favor of the more physically descriptive term "albedo modification" to describe a subset of such techniques that seek to enhance the reflectivity of the planet to cool the global temperature. Other related methods that modify the emission of infrared energy to space to cool the planet are also discussed in the second volume.

Transparency in discussing this subject is critical. In that spirit of transparency, this study was based on peer-reviewed literature and the judgments of the committee members involved; no new research was done as part of this study and all data and information used in this study are from entirely open sources. Moving forward, the committee hopes that these two new reports will help foster an ethos in which all research in this area is conducted openly, responsibly, and with transparent goals and results.

It is the committee's sincere hope that these topics will receive the attention and investment commensurate with their importance to addressing the coming potential climate crises. By helping to bring light to this topic area, carbon dioxide removal tech-

nologies could become one more viable strategy for addressing climate change, and leaders will be far more knowledgeable about the consequences of albedo modification approaches before they face a decision whether or not to use them.

In closing, I would like to thank my fellow committee members for all of their hard work to summarize the existing, fragmented science and to work toward consensus on extremely complex issues. As well, we greatly appreciate all of the time and effort volunteered by our colleagues who generously gave their time and talent to review these reports, speak at our committee meetings, and communicate with us during the study process. We would also like to thank the NRC staff for their superb efforts to assemble and make sense of the many moving parts of two separate reports.

Marcia McNutt, *Chair*
Committee on Geoengineering Climate:
Technical Evaluation and Discussion of Impacts

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their review of this report:

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Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the views of the committee, nor did they see the final draft of the report before its release. The review of this report was overseen by **Warren M. Washington**, National Center for Atmospheric Research, Boulder, Colorado, and **James W. C. White**, University of Colorado, Boulder; appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

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Summary

Our planet has entered a period in which its climate is changing more rapidly than ever experienced in recorded human history, primarily caused by the rapid buildup of carbon dioxide (CO₂) in the atmosphere from the burning of fossil fuels. Scientists have identified a number of risks from changing climate, including rising sea level, drought, heat waves, more severe storms, increasing precipitation intensity, and associated disruption of terrestrial and aquatic ecosystems. Additionally, elevated atmospheric CO₂ is diffusing into the ocean, measurably acidifying surface waters and affecting marine ecosystems. Natural processes currently remove about half of our emissions from the atmosphere each year. Once emissions cease, it will take thousands of years before those processes eventually return Earth to something like preindustrial levels of atmospheric CO₂.

The two main options for responding to the risks of climate change involve mitigation—reducing and eventually eliminating human-caused emissions of CO₂ and other greenhouse gases (GHGs)—and adaptation—reducing the vulnerability of human and natural systems to changes in climate. A third potentially viable option, currently under development but not yet widely deployed, is carbon dioxide removal (CDR) from the atmosphere accompanied by reliable sequestration. A fourth, more speculative family of approaches called albedo modification seeks to offset climate warming by greenhouse gases by increasing the amount of sunlight reflected back to space.¹ Albedo modification techniques mask the effects of greenhouse warming; they do not reduce greenhouse gas concentrations (see Box S.1 for definitions of key terms).

The Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts was charged with conducting a technical evaluation of a limited number of “geoengineering” (also known as “climate engineering”) techniques that have been proposed so far and commenting generally on the potential impacts of deploying these technologies, including possible environmental, economic, and national security concerns. The committee prefers the term “climate intervention” because “geoengineering” has other meanings in the context of geological engineering. Furthermore, the term “engineering” implies a more precisely tailored and controllable process than might be the case for these climate interventions.

¹ Another speculative approach that seeks to make cirrus clouds thinner to increase the infrared thermal energy returned to space is considered alongside albedo modification approaches.

BOX S.1 DEFINITIONS OF KEY TERMS USED IN THE REPORTS

Climate Intervention—purposeful actions intended to produce a targeted change in some aspect of the climate (e.g., global mean or regional temperature); includes actions designed to remove carbon dioxide or other greenhouse gases from the atmosphere or to change Earth’s radiation balance (referred to as “albedo modification”), but not efforts to limit emissions of greenhouse gases (i.e., climate mitigation).

Carbon Dioxide Removal—intentional efforts to remove carbon dioxide from the atmosphere, including land management strategies, accelerated weathering, ocean iron fertilization, bioenergy with carbon capture and sequestration, and direct air capture and sequestration. CDR techniques complement carbon capture and sequestration methods that primarily focus on reducing CO₂ emissions from point sources such as fossil fuel power plants.

Albedo Modification—intentional efforts to increase the amount of sunlight that is scattered or reflected back to space, thereby reducing the amount of sunlight absorbed by Earth, including injecting aerosols into the stratosphere, marine cloud brightening, and efforts to enhance surface reflectivity.

This study was supported by the National Academy of Sciences, the U.S. intelligence community, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and the Department of Energy (the statement of task for the committee can be found in Appendix A). This summary presents overarching conclusions from a pair of reports the committee authored in response to its charge. These reports are intended to provide a thoughtful, clear scientific foundation that informs ethical, legal, and political discussions surrounding these potentially controversial topics.

**CARBON DIOXIDE REMOVAL AND ALBEDO MODIFICATION
WITHIN A PORTFOLIO OF CLIMATE RESPONSES**

There is no substitute for dramatic reductions in the emissions of CO₂ and other greenhouse gases to mitigate the negative consequences of climate change and, concurrently, to reduce ocean acidification. Mitigation, although technologically feasible, has been difficult to achieve for political, economic, and social reasons that may persist well into the future. Whatever we do as a society, some adaptation will be necessary, but the degree to which it is needed depends on the amount of climate change and the degree to which future emissions of CO₂ and other GHGs (henceforth in this context the committee often mentions only CO₂ as it has the largest climate impact) are reduced. Although there are ongoing efforts at climate adaptation in many

communities, both humans and ecosystems face substantial challenges in adapting to the varied impacts of climate change over the coming century. For that reason, it may be prudent to examine additional options for limiting the risks from climate change (namely CDR and albedo modification), which could contribute to a broader portfolio of responses, even as mitigation and adaptation remain the primary emphasis. The committee evaluated CDR and albedo modification within this broader portfolio of climate response.

The deployment of any climate response strategy requires consideration of many factors: How effective is the strategy at achieving predictable and desirable outcomes? How much does the strategy cost to implement at a scale that matters? What are the risks for unintended consequences and opportunities for co-benefits? What governance mechanisms are in place or are needed to ensure that safety, equity, and other ethical aspects are considered (e.g., intergenerational implications)?

As the committee analyzed these factors for specific CDR and albedo modification strategies, it became apparent that there are vast differences in the inherent characteristics of the two approaches. CDR seeks to mitigate the primary *causes* of present climate change by reducing the amount of CO₂ in the atmosphere. Albedo modification seeks to offset some of the climatic *effects* of high greenhouse gas concentrations but does not address the greenhouse gas concentrations themselves. The research needs, environmental risks, and political ramifications associated with albedo modification are dramatically different from those associated with carbon dioxide removal (see Table S.1).

Recommendation 1: Efforts to address climate change should continue to focus most heavily on mitigating greenhouse gas emissions in combination with adapting to the impacts of climate change because these approaches do not present poorly defined and poorly quantified risks and are at a greater state of technological readiness.

CARBON DIOXIDE REMOVAL READY FOR INCREASED RESEARCH AND DEVELOPMENT

Some CDR strategies seek to sequester carbon in the terrestrial biosphere or the ocean by accelerating processes that are already occurring as part of the natural carbon cycle and which already remove significant quantities of CO₂ from the atmosphere. These approaches have challenges and risks that need to be assessed, including verifying and monitoring the amount of carbon removed, incomplete understanding

TABLE S.1 Overview of General Differences Between Carbon Dioxide Removal Proposals and Albedo Modification Proposals

Carbon dioxide removal proposals...	Albedo modification proposals...
... address the cause of human-induced climate change (high atmospheric GHG concentrations).	...do not address cause of human-induced climate change (high atmospheric GHG concentrations).
...do not introduce novel global risks.	... introduce novel global risks.
...are currently expensive (or comparable to the cost of emission reduction).	...are inexpensive to deploy (relative to cost of emissions reduction).
...may produce only modest climate effects within decades.	...can produce substantial climate effects within years.
...raise fewer and less difficult issues with respect to global governance.	...raise difficult issues with respect to global governance.
...will be judged largely on questions related to cost.	...will be judged largely on questions related to risk.
...may be implemented incrementally with limited effects as society becomes more serious about reducing GHG concentrations or slowing their growth.	...could be implemented suddenly, with large-scale impacts before enough research is available to understand the risks relative to inaction.
...require cooperation by major carbon emitters to have a significant effect.	...could be done unilaterally.
...for likely future emissions scenarios, if abruptly terminated would have limited consequences.	...for likely future emissions scenarios, if abruptly terminated would produce significant consequences.

NOTE: GHG stands for greenhouse gases released by human activities and natural processes and includes carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and others. The committee intends to limit discussion to proposals that raise the fewest problematic issues, thus excluding ocean iron fertilization from the CDR list. Each statement may not be true of some proposals within each category.

of how long carbon may be sequestered before possible rerelease to the atmosphere, unintended effects such as the release of other greenhouse gases that can partially offset or even cancel out the climate benefits from carbon sequestration, and expanded competition for resources such as land and freshwater. In general, published estimates show that land management and reforestation can remove significant

amounts of CO₂ from the atmosphere and can often generate substantial co-benefits. On the other hand, previous studies nearly all agree that deploying ocean iron fertilization at climatically relevant levels poses risks that outweigh potential benefits. However, there may be other methods to enhance uptake of CO₂ through accelerated weathering cycles on land and in the ocean that are more environmentally benign and thus worth pursuing.

Other CDR approaches involve capturing CO₂ from the atmosphere and disposing of it by pumping it underground at high pressure. These include bioenergy with carbon capture and sequestration (BECCS), which uses plants to remove the CO₂ from the air, and direct air capture and sequestration (DACs), which includes various techniques to scrub CO₂ directly from ambient air. Proposals to capture CO₂ from the atmosphere have challenges and uncertainties including cost and maximum scale of feasible deployment. Removing CO₂ from ambient air is more difficult than removing CO₂ from the stack gas of power plants that burn conventional fuel or biomass because of its much lower concentration in ambient air; thus, it will involve higher costs in most circumstances. CDR approaches such as DACs and BECCS require reliable long-term disposal or sequestration of carbon to prevent its return to the atmosphere. Reliable disposal has challenges, environmental risks, and uncertainties, including cost, long-term monitoring, potential induced seismicity, and leakage.

The barriers to deployment of CDR approaches are largely related to slow implementation, limited capacity, policy considerations, and high costs of presently available technologies. Additional research and analysis will provide information to help address those challenges. For these reasons, if carbon removal technologies are to be widely deployed, it is critical to embark now on a research program to lower the technical barriers to efficacy and affordability. In the end, any actions to decrease the excess burden of atmospheric CO₂ serve to decrease, or at least slow the onset of, the risks posed by climate change. Environmental risks vary among CDR approaches but are generally much lower than the risks associated with albedo modification approaches. However, it is also less risky environmentally to avoid a given CO₂ emission to the atmosphere than to emit it with the expectation that it will be purposefully removed from the atmosphere at some later time. Developing the ability to capture and reliably and safely dispose of climatically important amounts of atmospheric CO₂ requires research into how to make the more promising options more effective, more environmentally friendly, and less costly. Such research investments would accelerate this development and could help avoid some of the greatest climate risks that the current carbon emission trajectory poses.

Recommendation 2: The committee recommends research and development investment to improve methods of carbon dioxide removal and disposal at scales that would have a global impact on reducing greenhouse warming, in particular to minimize energy and materials consumption, identify and quantify risks, lower costs, and develop reliable sequestration and monitoring.

- It is increasingly likely that, as a society, we will need to deploy some forms of CDR to avoid the worst impacts of climate change, but without research investment now such attempts at climate mitigation are likely to fall well short of needed targets.
- Many CDR strategies provide viable and reasonably low-risk approaches to reducing atmospheric concentrations of CO₂. Because the rate of CO₂ removal is inherently slow, CDR must be sustained at large scales over very long periods of time to have a significant effect on CO₂ concentrations and the associated risks of climate change.
- Absent some new technological innovation, large-scale CDR techniques have costs comparable to or exceeding those of avoiding carbon dioxide emissions by replacing fossil fuels with low-carbon energy sources. Widespread CDR deployment would likely occur in a policy environment in which there are limits or a price is imposed on emissions of carbon dioxide, and in that case CDR will compete directly with mitigation on a cost basis (i.e., cost per ton of CO₂ removed versus cost per ton of CO₂ emission avoided).
- Decisions regarding deployment of CDR will be largely based on cost and scalability. Carbon dioxide removal strategies might entail some local or even regional environmental risk, but in some cases, CDR strategies may have also substantial co-benefits.
- Several federal agencies should have a role in defining and supporting CDR research and development. The committee recommends a coordinated approach that draws upon the historical strength of the various agencies involved and uses existing coordination mechanisms, such as the U.S. Global Change Research Program, to the extent possible.

ALBEDO MODIFICATION PRESENTS POORLY UNDERSTOOD RISKS

Proposed albedo modification approaches introduce environmental, ethical, social, political, economic, and legal risks associated with intended and unintended consequences. However, there are both theoretical and observational reasons to believe that albedo modification has the potential to rapidly offset some of the consequences of global warming at an affordable cost. If less energy from the Sun is absorbed by the

Earth system, the surface of Earth will cool on average. This is clearly demonstrated by the history of past volcanic eruptions. For example, the eruption of Mount Pinatubo in the Philippines in June of 1991 injected 20 million tons of sulfur dioxide into the stratosphere, which increased Earth's reflectivity (albedo) and decreased the amount of sunlight absorbed, causing globally averaged surface air temperatures to cool an estimated 0.3°C for a period of 3 years. Such cooling can take place rapidly, within a year of the change in albedo, but only lasts for a few years unless additional material is injected. Increasing the reflectivity of low clouds is another strategy that might be able to cool the planet within a year or two from the onset of the intervention.

Modeling studies indicate that significant cooling, equivalent in amplitude to the warming produced by doubling the CO₂ concentration in the atmosphere, can be produced by the introduction of tens of millions of tons of aerosol-forming gases into the stratosphere. Although there are many reasons to be cautious in interpreting model results, climate simulations can extend scientific understanding of albedo modification to timescales beyond those observed with volcanic eruptions. Modeling results also suggest that the benefits and risks will not be uniformly distributed around the globe.

Feasibility studies (based on models, as yet untested in the field) suggest that it may be possible to introduce aerosols into the stratosphere that can produce significant reduction in incoming sunlight (1 W/m² or more) with few if any major technological innovations required. Direct costs of deployment of a stratospheric aerosol layer of sufficient magnitude to offset global mean radiative forcing of CO₂ have been estimated to be at least an order of magnitude less than the cost of decarbonizing the world's economy. Although these cost estimates do not include an appropriate monitoring system or indemnification for damages from albedo modification actions, they are small enough that decisions are likely to be based primarily on considerations of potential benefits and risks, and not primarily on the basis of direct cost.

Albedo modification presents a number of risks and expected repercussions. Observed effects from volcanic eruptions include stratospheric ozone loss, changes to precipitation (both amounts and patterns), and likely increased growth rates of forests caused by an increase in diffuse solar radiation. Large volcanic eruptions are by their nature uncontrolled and short lived, and have in rare cases led to widespread crop failure and famine (e.g., the Tambora eruption in 1815). However, effects of a sustained albedo modification by introduction of aerosol particles may differ substantially from effects of a brief volcanic eruption. Models also indicate that there would be consequences of concern, such as some ozone depletion or a reduction in global precipitation associated with sustained albedo modification. Furthermore, albedo modification

does nothing to reduce the buildup of atmospheric CO₂, which is already changing the makeup of terrestrial ecosystems and causing ocean acidification and associated impacts on oceanic ecosystems.

Another risk is that the success of albedo modification could reduce the incentive to curb anthropogenic CO₂ emissions and that albedo modification would instead be deployed with ever increasing intensity. The committee considers it to be irrational and irresponsible to implement sustained albedo modification without also pursuing emissions mitigation, carbon dioxide removal, or both. Climate models indicate that the combination of large-scale albedo modification with large-scale CO₂ increases could lead to a climate with different characteristics than the current climate. Without reductions in CO₂ levels in the atmosphere, the amount of albedo modification required to offset the greenhouse warming would continue to escalate for millennia, generating greater risks of negative consequences if it is terminated for any reason (e.g., undesirable side effects, political unrest, and cost), because the effects of the forcing from the CO₂ concentrations present at the time of termination will be rapidly revealed.

It is not possible to quantify or even identify other environmental, social, political, legal, and economic risks at this time, given the current state of knowledge about this complex system. The uncertainties in modeling of both climate change and the consequences of albedo modification make it impossible today to provide reliable, quantitative statements about relative risks, consequences, and benefits of albedo modification to the Earth system as a whole, let alone benefits and risks to specific regions of the planet. To provide such statements, scientists would need to understand the influence of various possible activities on both clouds and aerosols, which are among the most difficult components of the climate system to model and monitor. Introducing albedo modification at scales capable of substantial reductions in climate impacts of future higher CO₂ concentrations would be introducing a novel situation into the Earth system, with consequences that are poorly constrained at present.

Gaps in our observational system also present a critical barrier to responsible deployment of albedo modification strategies. Currently, observational capabilities lack the capacity to monitor the evolution of an albedo modification deployment (e.g., the fate of the aerosols and secondary chemical reactions), its effect on albedo, or its environmental effects on climate or other important Earth systems. Finally, an international forum for cooperation and coordination on any sort of climate intervention discussion and planning is lacking.

Recommendation 3: Albedo modification at scales sufficient to alter climate should not be deployed at this time.

- Albedo modification strategies for offsetting climate impacts of high CO₂ concentrations carry risks that are poorly identified in their nature and unquantified.
- Deployment at climate-altering amplitudes should only be contemplated armed with a quantitative and accurate understanding of the processes that participate in albedo modification. This understanding should be demonstrated at smaller scales after intended and unintended impacts to the Earth system have been explicitly documented, both of which are lacking.
- There is significant potential for unanticipated, unmanageable, and regrettable consequences in multiple human dimensions from albedo modification at climate-altering scales, including political, social, legal, economic, and ethical dimensions.
- Current observing systems are insufficient to quantify the effects of any intervention. If albedo modification at climate-altering scales were ever to occur, it should be accompanied by an observing system that is appropriate for assessing the impacts of the deployment and informing subsequent actions.
- If research and development on albedo modification were to be done at climate-altering scales, it should be carried out only as part of coordinated national or international planning, proceeding from smaller, less risky to larger, more risky projects; more risky projects should be undertaken only as information is collected to quantify the risks at each stage.

THE NEED FOR MORE RESEARCH ON ALBEDO MODIFICATION

There are many research opportunities that would allow the scientific community to learn more about the risks and benefits of albedo modification, knowledge which could better inform societal decisions without imposing the risks associated with large-scale deployment. There are several hypothetical, but plausible, scenarios under which this information would be useful. For example:

- If, despite mitigation and adaptation, the impacts of climate change still become intolerable (e.g., massive crop failures throughout the tropics), society would face very tough choices regarding whether and how to deploy albedo modification until such time as mitigation, carbon dioxide removal, and adaptation actions could significantly reduce the impacts of climate change.
- The international community might consider a gradual phase-in of albedo modification to a level expected to create a detectable modification of Earth's

climate, as a large-scale field trial aimed at gaining experience with albedo modification in case it needs to be scaled up in response to a climate emergency. This might be considered as part of a portfolio of actions to reduce the risks of climate change.

- If an unsanctioned act of albedo modification were to occur, scientific research would be needed to understand how best to detect and quantify the act and its consequences and impacts.

In any of these scenarios, better understanding of the feasibility, verifiability, consequences (intended and unintended), and efficacy of proposed albedo modification strategies would be critical. Indeed, current implementation options are clearly crude and developing better methods in advance of any future development would provide less risky options for society and state actors to consider. There is a risk that research on albedo modification could distract from efforts to mitigate greenhouse gas emissions. This “moral hazard” risk may have kept more albedo modification research from being done up to now. The committee argues that, as a society, we have reached a point where the severity of the potential risks from climate change appears to outweigh the potential risks from the moral hazard associated with a suitably designed and governed research program. Hence, it is important to understand whether and to what extent albedo modification techniques are viable.

Much of the required research on albedo modification overlaps considerably with the basic scientific research that is needed to improve understanding of the climate system. Examples of such “multiple benefit research”—research that can contribute to a better understanding of the viability of albedo modification techniques and also a better understanding of basic climate science—include conducting research on clouds and aerosols, maintaining the continuity of measurement of the top-of-atmosphere radiation budget, and monitoring ocean-atmosphere energy exchange through programs such as the Argo float system. Of necessity, much of this multiple-benefit research would be part of a comprehensive climate research portfolio or research program aimed at other purposes (e.g., effect of volcanic eruptions on aerosols). In addition, the committee argues that research topics specific to albedo modification should also be identified and prioritized as part of a larger research effort and tasked to the relevant federal agencies for possible support within existing or expanded research programs.

Recommendation 4: The committee recommends an albedo modification research program be developed and implemented that emphasizes multiple-benefit research that also furthers basic understanding of the climate system and its human dimensions.

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- If future decision makers reach a point that they are contemplating adopting albedo modification, or assessing such an adoption by others, they will need to assess a wide range of factors, both technical and social, to compare the potential benefits and risks of an albedo modification deployment. These factors would include an assessment of the expected climate with only emissions reductions and CDR (including risks from continued greenhouse gas emissions with no intervention), the expected effects from starting albedo modification, the expected effects from terminating albedo modification, ethical issues, and social responses.
 - The goal of the research program should be to improve understanding of the range of climate and other environmental effects of albedo modification, as well as understanding of unintended impacts.
 - U.S. research on albedo modification should be supported by a number of scientific research agencies in a coordinated manner. The U.S. Global Change Research Program could provide valuable oversight and coordination to ensure that the aspects of the research that are of benefit to both basic climate science and understanding of albedo modification are taken into account.
 - Small-scale field experiments with controlled emissions may for some situations with some forms of intervention be helpful in reducing model uncertainties, validating theory, and verifying model simulations in different conditions. Experiments that involve release of gases or particles into the atmosphere (or other controlled perturbations) should be well-enough understood to be benign to the larger environment, should be conducted at the smallest practical scales, should be designed so as to pose no significant risk, and should be planned subject to the deliberative process outlined in Recommendation 6.

Recommendation 5: The committee recommends that the United States improve its capacity to detect and measure changes in radiative forcing and associated changes in climate.

- A new generation of short-wavelength (albedo) and long-wavelength (outgoing infrared) space-based instruments should be developed and deployed that can measure radiative forcing with an accuracy of better than 1 W/m^2 , including hyperspectral instruments that could improve discrimination of the processes that cause changes in radiative forcing. Such instruments would significantly improve understanding of the effects of clouds and stratospheric aerosols on climate, improve the ability to predict the effects of albedo modification, and provide an ability to detect large-scale albedo modification by unilateral and uncoordinated actors.

- An observational capability should be developed to make better use of future major volcanic eruptions to improve understanding of the effects of stratospheric aerosols on climate. This would involve space-based sensors and rapidly deployable ground-based and airborne sensors for monitoring stratospheric aerosols.

GOVERNANCE CONSIDERATIONS

Some types of research into intentional albedo modification will likely have legal, ethical, social, political, economic, and other important ramifications. Albedo modification research must abide by existing laws, regulations, and policies that apply to research broadly and its impacts on worker safety, the environment, and human and animal welfare. However, such research is not specifically addressed by any federal laws or regulations.

Given the perceived and real risks associated with some types of albedo modification research, open conversations about the governance of such research, beyond the more general research governance requirements, could encourage civil society engagement in the process of deciding the appropriateness of any research efforts undertaken.

“Governance” is not a synonym for “regulation.” Depending on the types and scale of the research undertaken, appropriate governance of albedo modification research could take a wide variety of forms ranging from the direct application of existing scientific research norms, to the development of new norms, to mechanisms that are highly structured and extensive. The most appropriate type of governance structures for albedo modification research will potentially depend on the nature and scale of that research. It is not the purview of the committee to make an assessment or recommendation of the appropriate structure. However, the committee does believe that governance considerations should be targeted at ensuring civil society involvement in decision making through a transparent and open process. It should focus on enabling safe and useful research on the viability and impacts of albedo modification strategies. Ultimately, the goal is to ensure that the benefits of the research are realized to inform civil society decision making, the associated challenges are well understood, and risks are kept small.

Recommendation 6: The committee recommends the initiation of a serious deliberative process to examine (a) what types of research governance, beyond those that already exist, may be needed for albedo modification research, and (b) the types of research that would require such governance, potentially based on the magnitude

of their expected impact on radiative forcing, their potential for detrimental direct and indirect effects, and other considerations.

- If a new governance structure is determined to be needed based on deliberations among governance experts and civil society representatives, the development of the governance structure should consider the importance of being transparent and having input from a broad set of stakeholders to ensure trust among the stakeholders and appropriate consideration of all dimensions.
- Such a governance structure should consider setting clear and quantitative guidelines for experimentation and be responsive to domestic and international laws and treaties.
- The deliberative process should consider focusing on research activities that involve injecting material into the atmosphere, for example aerosol-producing substances injected into the upper atmosphere or cloud-brightening substances injected near the surface.
- If a program of research in albedo modification includes controlled-emission experiments, it should provide for a sufficiently specific governance regime to at least define the scale of experiments at which oversight begins.
- The approach to governance should consider the need for increasing supervision as the scope and scale of the research and its potential implications increase, including the amount of material emitted, the area affected, and the length of time over which emission continues.
- The goal of the governance should be to maximize the benefits of research while minimizing risks.
- The United States should help lead the development of best practices or specific norms that could serve as a model for researchers and funding agencies in other countries and could lower the risks associated with albedo modification research.

CONCLUDING THOUGHTS

Addressing the challenges of climate change requires a portfolio of actions that carry varying degrees of risk and efficacy. CDR strategies and other technologies and approaches that reduce net emissions (e.g., carbon capture and sequestration, non-carbon-based energy, and energy efficiency improvements) offer the potential to slow the growth and reverse the increase of CO₂ concentrations in the atmosphere. The lowest-risk CDR strategies are currently limited by cost and at present cannot achieve the desired result of removing climatically important amounts of CO₂ beyond the significant removal already performed by natural processes. However, with declining

costs and stronger regulatory commitment, atmospheric CO₂ removal could become a valuable component of the portfolio of long-term approaches to reducing CO₂ concentrations in the atmosphere and associated impacts. Overall, there is much to be gained and very low risk in pursuing multiple parts of a portfolio of CDR strategies that demonstrate practical solutions over the short term and develop more cost-effective, regional-scale and larger solutions for the long term.

In contrast, even the best albedo modification strategies are currently limited by unfamiliar and unquantifiable risks and governance issues rather than direct costs. The committee reiterates that it is opposed to climate-altering deployment of albedo modification techniques, but it does recommend further research, particularly multiple-benefit research that furthers the basic understanding of the climate system and seeks to quantify the potential costs, consequences (intended and unintended), and risks from these proposed albedo modification techniques.

Climate change is a global challenge that will require complex and comprehensive solutions, which in turn will require that people of many nations work together toward common objectives. For the outcome to be as successful as possible, any climate intervention research should be robust, open, likely to yield valuable scientific information, and international in nature. The impacts of any potential future climate interventions should be honestly acknowledged and fairly considered. The committee firmly believes that there is no substitute for dramatic reductions in CO₂ emissions to mitigate the negative consequences of climate change at the lowest probability of risk to humanity. However, if society ultimately decides to intervene in Earth's climate, the committee most strongly recommends any such actions be informed by a far more substantive body of scientific research than is available at present.

Introduction

For more than three decades, scientists have predicted that a doubling of carbon dioxide in Earth's atmosphere from preindustrial levels would warm Earth's surface by an average of between 1.5°C and 4.5°C (about 3°F to 8°F). The latest report from the Intergovernmental Panel on Climate Change (IPCC) confirms this finding, with greater confidence, and furthermore affirms that the primary cause of the observed increase in global-average temperature is anthropogenic greenhouse gas (GHG) emissions (IPCC, 2013b). The IPCC further concludes that, if current emissions trends continue, by the end of the century the planet will experience a warming of up to 5°C (Figure 1.1), sea level will rise by as much as 1 m (Figure 1.2), and the Arctic will be ice free in the summer by midcentury. As part of this change in climate, society will experience an increase in the frequency and severity of heat waves, droughts, and heavy precipitation events (also see NCA, 2014).

To date, scientists have observed a number of manifestations of the changing climate, all of which will likely be amplified in the future (IPCC, 2014b). Moreover, the ability to predict these changes carries considerable uncertainties that suggest that while the adverse effects of climate change may not be as severe as many predictions, it is also quite possible that they may in fact be considerably worse (NRC, 2013a). One very visible example is the reduction in Arctic perennial sea ice cover, which has diminished at a rate of 13 percent per decade (relative to the 1979-2012 mean; see Fetterer et al., 2012; Stroeve et al., 2012b). This reduction in ice cover far exceeded model predictions (Stroeve et al., 2012a) and serves as a stark indication that the challenges we may face with climate change may occur sooner rather than later. Such a circumstance underscores the potential mismatch between the timescales at which detrimental change may occur and the timescales at which meaningful mitigation strategies may be implemented.

Globally, greenhouse gas emissions have been increasing as the growing demand for energy has more than offset what progress there has been from improved efficiency and deployment of new energy sources with lower GHG emissions (Le Quéré et al., 2013). In May 2013 the CO₂ concentration measured at the Mauna Loa Observatory in Hawaii briefly exceeded 400 parts per million (ppm) for the first time in the modern era, before the spring bloom in the Northern Hemisphere temporarily drew down CO₂ levels (Figure 1.3). Concentrations of CO₂ in the atmosphere have been increasing from preindustrial levels of 280 ppm largely as the result of the combustion of

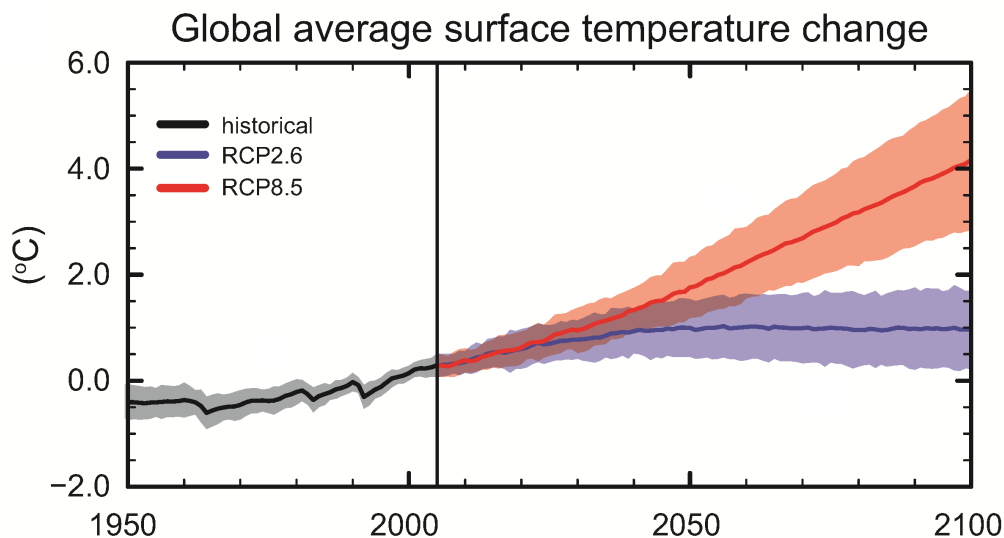


FIGURE 1.1 Temperature increase for various emission scenarios. A temperature rise of up to 5°C is possible by the end of the century if current emission trends continue. CMIP5 multimodel simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for two representative concentration pathway (RCP) scenarios, RCP2.6 (blue) and RCP8.5 (red). The RCP scenarios represent a family of hypothetical future scenarios for emission of CO₂ and other greenhouse gases. They are labeled according to the peak radiative forcing from all gases up to the year 2100, so that higher-numbered RCP scenarios correspond to climate futures with greater emissions. The full set of scenarios consists of RCP2.6, RCP4.5, RCP6.0, and RCP8.5, and the middle two have been selected for the analysis in this section. The RCP2.6 trajectory involves very aggressive emission mitigation and also requires negative emissions (e.g., carbon dioxide removal) to help meet its target. SOURCE: IPCC, 2013b, Fig. SPM.7.

fossil fuels. Unlike many other air pollutants—such as nitrogen oxides and sulfur oxides, which are removed by natural physical and chemical processes in just hours to days after they are emitted—the GHGs most responsible for causing climate change remain in the atmosphere for decades to centuries.¹ In order to stabilize or reduce atmospheric concentrations, and thus avoid the worst impacts of warming, global emissions of GHGs must be reduced by at least an order of magnitude (NRC, 2011a).

¹ Excess carbon is absorbed by the land biosphere and ocean over decades and centuries, and it reacts with carbonate and silicate materials over thousands of years; nevertheless, most of the excess carbon emitted today will still be in the atmosphere, land biosphere, or ocean many tens of thousands of years later, until geologic processes can form rocks and deposits that would incorporate this carbon (Archer et al., 2009; Berner et al., 1983).

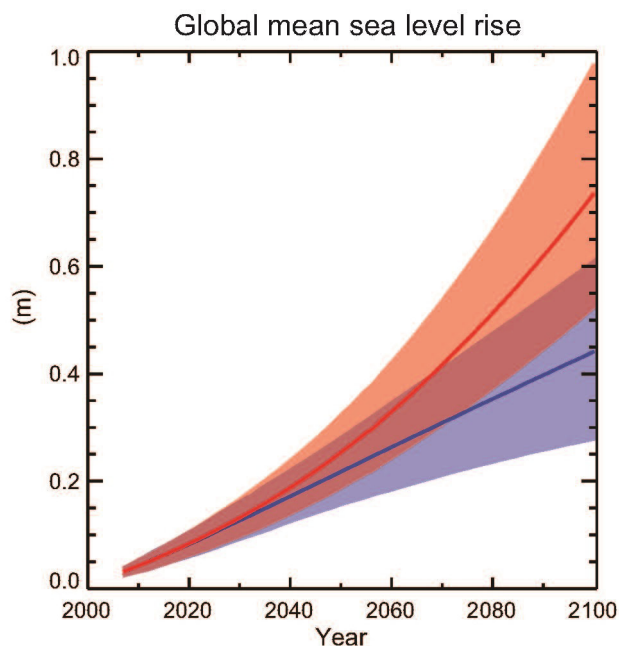


FIGURE 1.2 Sea level rise for emission scenarios RCP2.6 (blue) and RCP8.5 (red). A sea level rise of up to 1 m is possible by the end of the century if current emission trends continue. SOURCE: IPCC, 2013b, Fig. SPM.9.

To date, little progress has been made toward achieving such a major reduction (IPCC, 2011; NRC, 2010c).

Although many uncertainties remain in our understanding of climate science, it is clear that the planet is already experiencing significant climate change as a result of anthropogenic influences (IPCC, 2013b). To avoid greatly increased risk of damage from climate change, the international community has been called upon to embark on a major program to reduce emissions of carbon dioxide and other greenhouse gases (e.g., Hoffert et al., 1998; IPCC, 2013a, b, 2014a; NRC, 2011b). Because major actions to reduce emissions have been delayed, considerable additional climate change is inevitable (Cao et al., 2011). There is a portfolio of responses and proposed strategies for diminishing climate damage and risk (Figure 1.4). As outlined below in the section “Decarbonizing the Energy System,” implementing an aggressive program of emissions abatement or *mitigation* presents major challenges to how we live and function as a society. These challenges have to date been a major barrier to the undertaking of substantive steps to reduce greenhouse gas emission, even though doing so is technologically well within our grasp and constitutes the lowest-risk and most efficacious

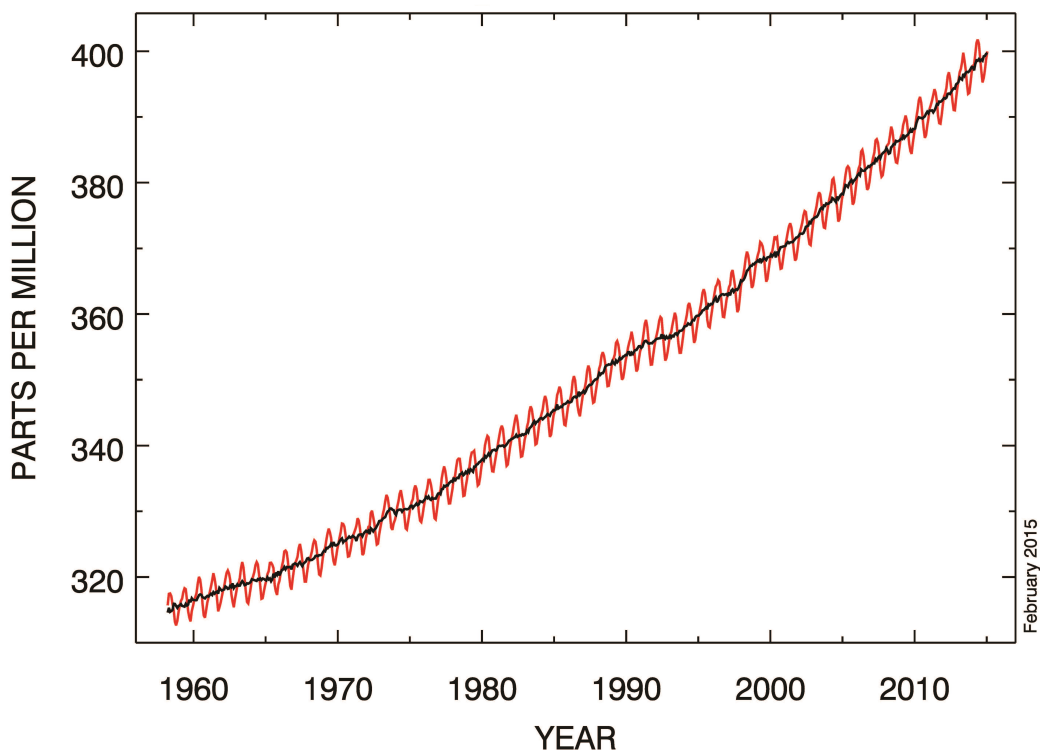


FIGURE 1.3 Record of the concentration of atmospheric carbon dioxide measured at the summit of Mauna Loa in Hawaii. The carbon dioxide data (red curve), measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO₂ in the atmosphere; the black curve represents the seasonally corrected data. The collection of this record was begun in 1958 by Charles David Keeling of the Scripps Institution of Oceanography. Today, similar trends are observed in locations all around the planet (see <http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/>). SOURCE: Scripps CO₂ Program.

path toward reducing the threats associated with anthropogenic climate change. Even if an aggressive global mitigation program is undertaken, substantial reductions in greenhouse gas levels would not be realized for several decades, and the halting or reversing of some of the detrimental effects already built into the climate system (e.g., ocean warming, ocean acidification, polar ice melting, sea level rise) would not follow for many decades or even centuries beyond that. Although there is considerable opportunity to limit the future growth of climate change, the world cannot avoid major climate change. As a result *adaptation* will be required and is indeed already happening (discussed below in “Adapting to Climate Change”). Adaptation will become increasingly costly and disruptive as the magnitude of climate change increases.

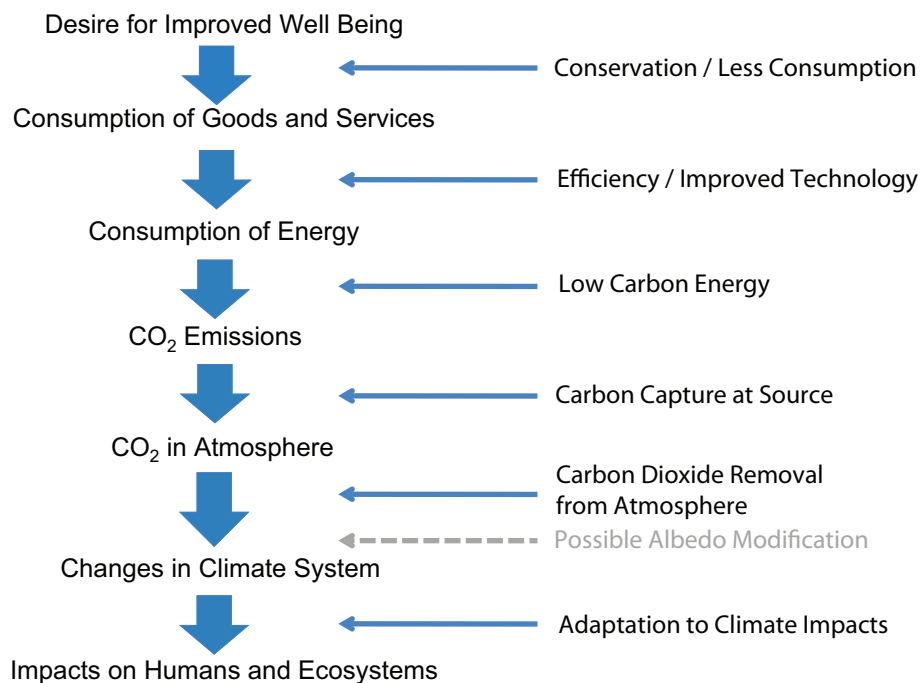


FIGURE 1.4 There is a portfolio of responses and proposed strategies for diminishing climate risk and damage at various steps in the causal chain of the human-climate system. Carbon dioxide removal approaches if proven effective could reduce the amount of CO₂ in the atmosphere. Albedo modification strategies have been proposed as a method to reduce the amount of warming that results from the accumulation of CO₂ in the atmosphere. SOURCE: Adapted from Caldeira et al., 2013.

This slow implementation of mitigation and the challenges of adaptation have led some people to consider whether strategies might exist to reduce the climate impacts of greenhouse gases after they have been emitted to the atmosphere. The committee refers to purposeful actions that are intended to produce a desired change in some aspect of the climate (e.g., global mean or regional temperature) as “climate intervention.” Climate intervention includes actions designed to remove carbon dioxide or other greenhouse gases from the atmosphere or to mask some of the climate effects of these gases by changing Earth’s radiation balance. This report examines approaches that actively increase the amount of short-wavelength radiation that is reflected to space, referred to as “albedo modification.” The terms “climate engineering” and “geoengineering” have been used to refer to highly heterogeneous and poorly defined collections of activities. The committee believes that these overarching terms

do little to advance the discussion of the set of activities under consideration here. Therefore, the committee refers instead to carbon dioxide removal (CDR) and albedo modification strategies independently. These two classes of strategies have very different characteristics (see Box 1.1).

The committee recognizes that altering Earth's albedo is an extreme measure, one that many already dismiss as unwise. However, the fact that the risks associated with climate change may themselves be unmanageable and irreversible through mitiga-

BOX 1.1 WHY THERE ARE TWO SEPARATE REPORTS

This committee was tasked with conducting a technical evaluation of examples of both carbon dioxide removal (CDR) techniques and albedo modification techniques (also known as "solar radiation management" or "sunlight reflection methods," both going by the initials SRM).^a

Some carbon dioxide removal techniques such as reforestation have already been considered in the public policy process as a form of mitigation—the effort to reduce net greenhouse gas emissions resulting from human activity. Linking direct air capture of carbon with carbon sequestration (DACs) has the potential to lead to a net reduction of CO₂ from the atmosphere if and when fossil fuel use is significantly reduced. As such, CDR approaches such as reforestation and DACs have more in common with widely discussed climate change mitigation approaches than they do with, for example, stratospheric aerosol injection. Reforestation and bioenergy with carbon capture and sequestration figured prominently in the IPCC Working Group III chapter on Mitigation of Climate Change, where mitigation is defined as "a human intervention to reduce the sources or enhance the sinks of greenhouse gases" (IPCC, 2014b).

In contrast, even the lowest-risk albedo modification approaches entail unknown and potentially large international political and environmental challenges, and therefore more research is required to better understand consequences of a possible implementation. The political ramifications, environmental risks, and research needs associated with albedo modification differ dramatically from those associated with carbon dioxide removal. Table S.1 summarizes the many contrasts in cost, risk, impact, and scale between these two approaches.

Although both share the goal of reducing the climate consequences of high greenhouse gas concentrations, CDR methods have more affinity with solutions aimed at reducing net anthropogenic CO₂ emissions (e.g., transitions to near-zero-emission energy systems), whereas albedo modification approaches aim to provide symptomatic relief from only some of the consequences of high greenhouse gas concentrations. The committee sees little benefit in or rationale for closely associating these carbon dioxide removal approaches with only distantly related and highly controversial albedo modification approaches. Therefore, the committee has decided that it can most effectively carry out its charge by producing two separate volumes: one on carbon dioxide removal and another on albedo modification.

^a Appendix A describes the charge to the committee for this study and Appendix B lists the committee membership.

tion efforts that are implemented too late makes examination of alternatives such as albedo modification a prudent action at this time, so that the limits and potential can at least be understood and weighed against the alternatives.

DECARBONIZING THE ENERGY SYSTEM

The most important human activity contributing to GHG emissions is the burning of fossil fuels (coal, oil, and natural gas) (IPCC, 2013b). Hence stabilizing or reducing atmospheric concentrations of carbon dioxide, and thus the climate, will require performing a massive transformation in the energy and transportation system (NRC, 2010b). Most knowledgeable observers understand that humanity should embark on an aggressive program to reduce emissions, although the scale of this challenge is underappreciated by some but not as daunting as it is made out to be by others.

According to the International Energy Agency (IEA), the total electricity consumption worldwide in 2011 was approximately 20,000 TWh (a rate of ~2,300 GW), and the United States accounted for just over 4,000 TWh (a rate of ~460 GW), or about 20%, of that amount (IEA, 2013). To gain some perspective on what will be involved in reducing fossil fuel dependence, a large power plant can produce about 1 GW of electrical power (EIA, 2013b; see also <http://www.eia.gov/electricity/annual/>), so the above numbers can be thought of as the amount of electricity produced by 2,300 large power plants globally or 460 large power plants for the United States alone. If society is to decarbonize the electricity system, it will be necessary to replace much of that infrastructure with carbon-free energy sources or to modify existing power plants to be carbon free. It took the United States more than five decades to create its existing electrical system infrastructure, and the lifetime for an existing coal-fired power plant is typically several decades (EIA, 2013a; Smil, 2010).

Further, global energy use is conservatively projected to rise between 15 percent and 30 percent by 2035 (from 2011 levels²), adding to the challenge of decarbonizing global energy. In addition to the electric power sector, the transportation, industrial and residential and commercial sectors currently account for the majority of energy use in the United States. As Figure 1.5 shows, energy input into electricity is only about 35 percent of U.S. total energy consumption. Most of the remainder involves the direct combustion of fossil fuels in transportation, heating and cooling of buildings, and industrial processes. In order to decarbonize the entire energy system, all of these

² 2011 total energy consumption = 8,918 Mtoe (million tons oil equivalent; 10,400 TWh); 2035 projections are between 10,390 and 11,750 Mtoe (12,100 and 13,700 TWh); <http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf>; accessed October, 2014.

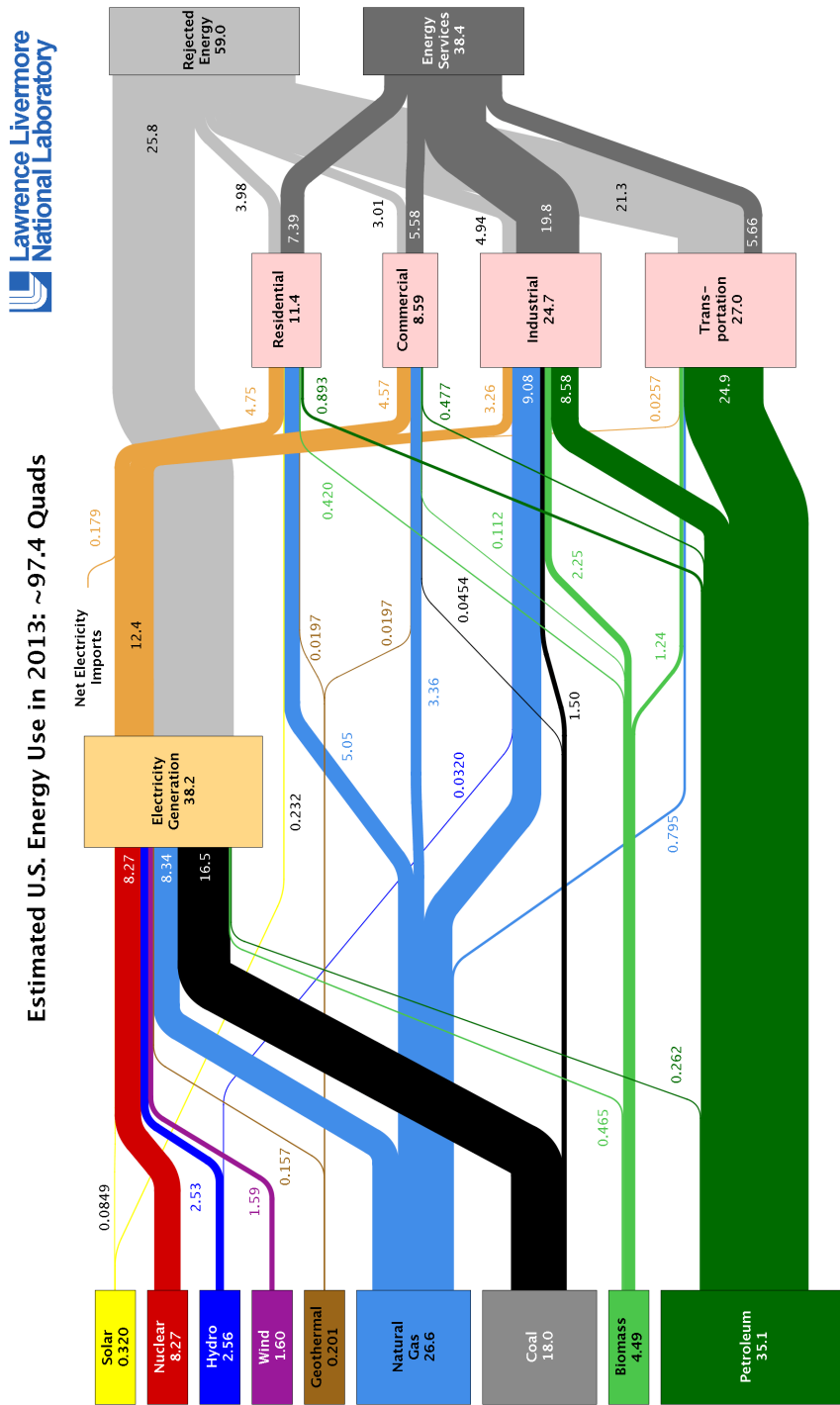


FIGURE 1.5 Flows of energy through the U.S. economy. The light gray bands on the right indicate energy that performs no useful service (i.e., waste). The dark gray bands on the right indicate energy that is used in the residential, commercial, industrial, and transportation sectors. Note that roughly 88 percent of the energy that presently enters the U.S. economy involves combustion of a fuel, which releases carbon dioxide to the atmosphere (1 quad is 10^{12} BTUs or 293 TWh). SOURCE: Lawrence Livermore National Laboratory, <https://flowcharts.llnl.gov/>.

applications will also need to be converted to systems that emit little or no carbon dioxide, in many cases by converting them to run on cleaner sources of electricity.

“Decarbonization” of the energy system could be facilitated by adopting the following strategies (IPCC, 2014b; NRC, 2010b):

1. Improve the efficiency with which the energy enters and is distributed within the system and increase the efficiency of all technologies that use energy.
2. Convert the electricity, residential, commercial, industrial, and transportation systems to sources of energy that release less carbon dioxide to the atmosphere. Examples of such sources could include nuclear energy; systems that capture and “sequester” carbon dioxide from power plants that use coal or natural gas; hydroelectricity, wind and solar power; some systems based on biomass (though not all bioenergy has low net carbon emissions); and geothermal energy.

A recent NRC report (2010b) assesses the feasibility of decarbonizing the energy system as follows:

There are large uncertainties associated with these sorts of projections, but the variation among them illustrates that the United States has many plausible options for configuring its future energy system in a way that helps meet GHG emissions-reduction goals. Note, however, that all cases involve a greater diversity of energy sources than exist today, with a smaller role for freely emitting fossil fuels and a greater role for energy efficiency, renewable energy, fossil fuels with CCS, and nuclear power. The virtual elimination by 2050 of coal without CCS—presently the mainstay of U.S. electric power production—in all the scenarios is perhaps the most dramatic evidence of the magnitude of the changes required. (NRC, 2010b)

Because they produce varying and intermittent power, it is thought that wind and solar cannot currently be the sole replacement for conventional fossil fuel–fired power plants. A reliable and affordable supply of carbon-free electricity will require a broad mix of generation types and energy sequestration approaches. Figure 1.6 shows three examples of potential scenarios for the mix of future generation types.

Although such estimates of future deployment of carbon-free energy sources indicate that it may be possible to achieve a decarbonized energy system, great uncertainties remain regarding the implementation of such scenarios due to factors such as costs, technology evolution, public policies, and barriers to deployment of new technologies (NRC, 2010b). Furthermore, simply accounting for the emissions from existing fossil fuel energy facilities over their remaining lifetime commits the planet to an additional

CLIMATE INTERVENTION: Carbon Dioxide Removal and Reliable Sequestration

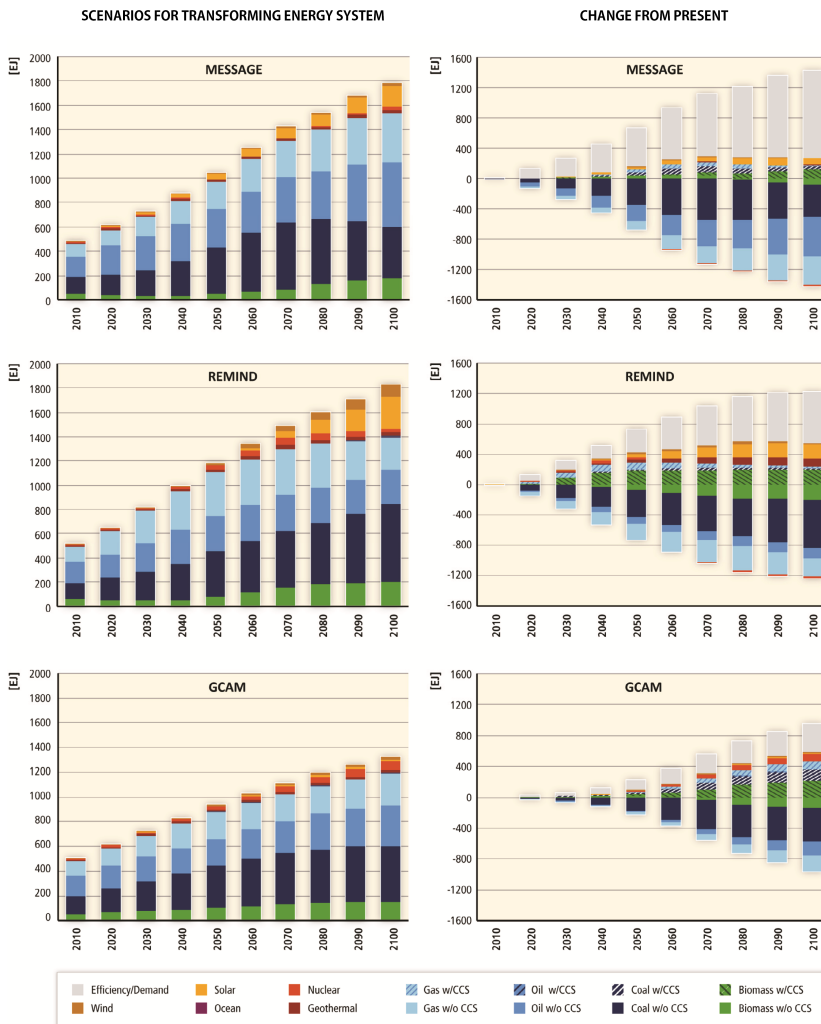


FIGURE 1.6 Three examples of alternative energy system transformation pathways are presented, where each pathway is consistent with limiting CO₂-equivalent (CO₂-eq) concentrations to about 480 ppm CO₂-eq by 2100. The scenarios from the three selected models (Model for Energy Supply Strategy Alternatives and their General Environmental Impact [MESSAGE], Regional Model of Investments and Development [ReMIND], and Global Change Assessment Model [GCAM]) show that there are different strategies for combining renewable and nonrenewable energy sources with increases in energy efficiency to meet the target. The left-hand panels show the energy supply for each scenario by year, which, in absence of new policies to reduce GHG emissions, would continue to be dominated by fossil fuels. Right-hand panels show alternative scenarios that limit GHG concentration to low levels through rapid and pervasive replacement of fossil fuels. Between 60 and 300 EJ of fossil fuels are replaced across the three scenarios over the next two decades (by 2030). By 2050 fossil energy use is 230-670 EJ lower than in non-climate policy baseline scenarios. SOURCE: IPCC, 2014b.

300 billion tons of CO₂ (Davis and Socolow, 2014).³ With whatever portfolio of technologies the transition is achieved, eliminating the carbon dioxide emissions from the global energy and transportation systems will pose an enormous technical, economic, and social challenge that will likely take decades of concerted effort to achieve.

ADAPTING TO CLIMATE CHANGE

The likely impacts of climate change have been described at length in reports of the IPCC (IPCC, 2013b; NRC, 2010a). Impacts likely to be experienced in the territories of the United States have been described in the U.S. National Climate Assessment (NCA, 2014) and the Arctic Assessment (ACIA, 2004; NRC, 2010a). These and similar studies conclude that, although it will be difficult and expensive, with a deliberate effort industrialized societies and economies can adapt to the climate change that may occur over the remainder of this century. There is much to do to build the capacity to adapt in the United States (NRC, 2010a, 2012a). The outlook is more pessimistic for the less industrialized societies and economies of the world, and grimmer still for many natural terrestrial, aquatic, and oceanic ecosystems (IPCC, 2013b).

The past 10,000 years have been a period of relative climatic stability that has allowed human civilization to flourish, agrarian sedentary communities to replace a nomadic lifestyle, and cities to emerge on mostly stable shorelines. This has been true despite notable exceptions, such as the Little Ice Age and episodes of volcanic-influenced weather that resulted in famine and widespread travail (Parker, 2013; Wood, 2014). What swings there have been in the global climate system have occurred within a relatively narrow range compared to those in the longer paleoclimate record. History suggests that some ancient civilizations have not adapted well to past climate changes. For example, it is believed that natural climate excursions, along with other factors, contributed to the end of the Anasazi and Mayan civilizations in the southwestern United States and Central America (Diamond, 2011; Tainter, 1988).

Globally, communities are already experiencing changing conditions directly linked to climate change—including rising seas that threaten low-lying island nations, loss of glaciers and sea ice and melting permafrost that expose Arctic communities to increased shoreline erosion, and consecutive record years of heat and drought stress (IPCC, 2013a,b, 2014a; NCA, 2014).

³ Units of mass adopted in this report follow the convention of the IPCC and are generally those which have come into common usage; GtCO₂ = gigatonnes of carbon dioxide, where 3.67 GtCO₂ = 1 GtC.

As described above, the challenge of decarbonizing the energy system is indeed daunting, and adapting to climate change is also likely to present substantial challenges. For example, much of the current infrastructure essential for commerce of coastal cities such as New York, Boston, Miami, Long Beach, Manhattan, New Orleans, Los Angeles, San Diego, and parts of San Francisco today could end up below sea level as the ocean continues to rise and, thus, could be submerged in the absence of protective dikes or other adaptive measures (NRC, 2012b; Strauss et al., 2012, 2013; Tebaldi et al., 2012). With sufficient planning, the possibility of moving infrastructure to higher ground is a cost-effective mitigation strategy for many localities, but there is little history of abandoning commercial use of coastal land in anticipation of sea level rise and there are many social and societal factors involved in potentially relocating communities (NRC, 2010a). Anticipatory adaptation is made more difficult because disruption to human lives and property typically does not occur gradually (see, for example, NRC, 2013a) but rather as a result of major weather events, such as hurricanes and other large storms, that cause billions of dollars in damage.

Food production is also sensitive to climate change. Although the relationship is complex—some regions will experience longer growing seasons while others will suffer from more heat stress—global yields of wheat, barley, and maize have decreased with increasing global-average temperature (Lobell and Field, 2007). There are numerous adaptation strategies that are available to cope with various climate changes—including changes to temperatures, precipitation, and ambient CO₂ concentrations—but all require substantial effort and investment (see Table 3.3 in NRC, 2010a). But even with adaptation, climate change can still cause long-term loss (for example, long-term loss of land due to sea level rise).

Shifts in mean temperature, temperature variability, and precipitation patterns are already causing stress on a diversity of ecosystems (NRC, 2013a). Species' range shifts have already become evident (Chen et al., 2011; Parmesan, 2006; Parmesan and Yohe, 2003; Poloczanska et al., 2013; Root et al., 2003; Staudinger et al., 2012) and are expected to accelerate with increasing rates of climate change, as are changes in the timing of species migrations (Gill et al., 2013) and other important plant and animal life-cycle events. The world's surface ocean has already experienced a 30 percent rise in acidity since the industrial revolution, and as that acidity continues to rise, there could potentially be major consequences to marine life and to the economic activities that depend on a stable marine ecosystem (NRC, 2013b). These impacts, combined with increasing numbers of exotic species introductions and demands on ecosystems to provide goods and services to support human needs, mean that extinction rates are increasing (Pimm, 2009; Staudinger et al., 2012). With continued climate change,

species will be increasingly forced to adapt to changing environmental conditions and/or migrate to new locations, or face increasing extinction pressures.

There are many climate adaptation and resilience efforts ongoing within the United States, often at the state or local levels (Boston Climate Preparedness Task Force, 2013; Miami-Dade County, 2010; PlaNYC, 2013; Stein et al., 2014; USGS, 2013; <http://www.cakex.org/>). Although this is a rapidly evolving field, there is still a great deal of research to be done in the field of climate adaptation and there may be insufficient capacity for adaptation (NRC, 2010a). Overall, both humans and ecosystems face substantial challenges in adapting to the varied impacts of climate change over the coming century.

CARBON DIOXIDE REMOVAL AND ALBEDO MODIFICATION

As discussed above, industrialized and industrializing societies have not collectively reduced the rate of growth of GHG emissions, let alone the absolute amount of emissions, and thus the world will experience significant and growing impacts from climate change even if rapid decarbonization of energy systems begins. Given the challenges associated with reducing GHG emissions and adapting to the impacts of climate change, some people have begun exploring whether there are climate intervention approaches that might provide additional mechanisms for facing the challenges of climate change.

In this volume, the committee considers strategies to remove GHGs (largely CO₂) from the atmosphere and provide reliable sequestration for it in perpetuity, which are termed CDR. Chapter 2 introduces several CDR approaches and Chapter 3 discusses each approach in more depth. While nature already performs “CDR” by removing the equivalent of more than half of our emissions from the atmosphere each year, all strategies considered for increasing CDR are inherently incremental and, as with most mitigation activities, require many parties to cooperate in order to have a global impact. With the exception of trying to increase uptake of carbon dioxide by fertilizing the ocean, most strategies for CDR, such as directly scrubbing carbon dioxide from the atmosphere, are local in scale. CDR technologies for removing carbon dioxide directly from the atmosphere at scale are unlikely to be energetically or financially advantageous over using carbon capture and sequestration technologies to remove carbon dioxide from stack gases associated with combusting fossil fuels or biomass (see discussion in Chapter 3 below). Thus, CDR may be more likely to be deployed to offset emissions from diffuse sources of carbon emissions (e.g., transport and agricultural activities). CDR is also likely to compete directly with other methods of reducing

or mitigating carbon dioxide emissions. On the margin the environmental value of removing a ton of carbon dioxide from the atmosphere is the same as that of avoiding the emission of a ton of carbon dioxide.⁴ Chapter 4 discusses some of the social and economic considerations surrounding CDR approaches. The balance between CDR and other mitigation methods is likely to be determined by the relative costs of the various technologies at the local and regional levels, together with government policies that limit or attach a price to GHG emissions. As a society, we need to better understand the potential cost and performance of CDR strategies for the same reason that we need to better understand the cost and performance of emission mitigation strategies—they may be important parts of a portfolio of options to stabilize and reduce atmospheric concentrations of carbon dioxide (see discussion in Chapter 5).

The companion volume to this report, *Climate Intervention: Reflecting Sunlight to Cool Earth*, considers strategies to increase the fraction of incoming solar radiation that is directly reflected back to space (increase the albedo) and related approaches that modify Earth's radiative balance. The introductory material for both reports is the same (Chapter 1 both reports). The concluding chapter of this volume (Chapter 5 below) summarizes the discussions in this volume; the concluding chapter of the companion volume summarizes both the discussions in that volume, as well as providing an overview of both volumes.

⁴ As discussed in Chapter 2, the removal of one ton of CO₂ from the atmosphere will lead to a reduction less than one ton in the CO₂ burden in the atmosphere due to a “rebound” effect where CO₂ outgasses from the ocean.

Carbon Dioxide Removal

In 1896 Svante Arrhenius wrote that human influence on the climate system might become noticeable over the course of the next millennium (Box 2.1). In less than 120 years, human activities—mostly fossil fuel burning and deforestation—resulted in the release of nearly two trillion tons of carbon dioxide (IPCC, 2013a), significantly increasing concentrations in the atmosphere (Figure 1.3) and generating urgent concern about climate change. Today, scientists, engineers, and policy makers are working together to discover, validate, and implement strategies to reduce CO₂ emissions as well as other greenhouse gases. As such, efforts to reduce anthropogenic CO₂ emissions to the atmosphere are likely to be a primary component within the portfolio of solutions to reduce climate change impacts (Figure 1.4). In addition, further mitigation options involving the removal of CO₂ from the atmosphere may provide cost-effective means to stabilize atmospheric CO₂ at concentrations that would limit adverse effects of global warming (IPCC, 2014a).

In the sections that follow, the committee discusses various potential methods for removing CO₂ from the atmosphere, together with estimates about possible rates of removal and total amounts that might be removed via these methods. To put these rates and totals in context, Table 2.1 summarizes human emissions of CO₂ and the associated increase of CO₂ in the atmosphere and CO₂ sinks since 1750 and in a recent 10-year period. Over the past decade, human activities have produced approximately 34 GtCO₂/yr annually with about 16 GtCO₂/yr, or about 2 ppm/yr, accumulating in the atmosphere (more recent estimates of annual emissions sources are ~39 GtCO₂/yr: 36 GtCO₂ from fossil fuel combustion and cement production and ~3 GtCO₂ from land use changes [Global Carbon Project, 2014]). Note that less than half of current and historical anthropogenic CO₂ emissions remain in the atmosphere; the remainder (18 GtCO₂/yr) has been taken up by the ocean and the terrestrial biosphere. This existing uptake and removal of CO₂ from air, natural “carbon dioxide removal” (CDR), already moderates the impacts of human emissions on atmospheric CO₂ levels and global climate. Indeed this uptake is seasonally so great that atmospheric CO₂ concentrations intra-annually decline (Figure 1.3). Nevertheless, substantially increasing existing CDR by natural or unnatural means such that the average annual growth rate of atmospheric CO₂ is reduced or reversed poses a significant challenge. One reason is that if enough CO₂ were removed from the atmosphere to cause a decline in overall atmospheric concentrations, CO₂ would “outgas” from the ocean into the atmosphere

BOX 2.1 HISTORICAL CONTEXT FOR CARBON DIOXIDE REMOVAL

Ever since the earliest realizations that atmospheric CO₂ influenced Earth's heat budget, there has been speculation that humankind could control carbon in order to control climate. Carbon dioxide removal has historical roots in the work of Swedish scientists Svante Arrhenius (1859-1927) and Nils Ekholm (1848-1923). In 1896, Arrhenius published a paper that examined the effect of different levels of atmospheric CO₂ concentration on the temperature of the planet. Using his energy budget model, he estimated that a 50 percent increase in CO₂ would raise global temperatures by about 3°C to 3.5°C, while a reduction of CO₂ by one-third would lower temperatures by roughly the same amount. His was in essence a geological model, used to examine the onset of ice ages and interglacials, in which he considered volcanoes and not coal burning to be the "chief source of carbonic acid for the atmosphere." However, since he estimated that burning the world's annual production of coal—at that point in time approximately 500 million tons—produced about one-thousandth of the total atmospheric concentration of carbon dioxide, he realized that humans could have a major influence over the course of a millennium (Arrhenius, 1896; Fleming, 1998).

In 1901, Ekholm suggested that human activity might someday play a major role in controlling Earth's temperature. He pointed out that over the course of a millennium the accumulation in the atmosphere of carbon dioxide from the burning of pit coal would "undoubtedly cause a very obvious rise of the mean temperature of the Earth." Ekholm suggested the grand possibility that by such means it might someday be possible "efficaciously to regulate the future climate of the Earth and consequently prevent the arrival of a new Ice Age." In this scenario, climate warming by enhanced coal burning would be pitted against the natural changes in Earth's orbital elements or the secular cooling of the sun (Ekholm, 1901; Fleming, 2000).

A half-century later, at a time when many scientists were beginning to express concern about the enhanced greenhouse effect, Caltech geochemist and futurist Harrison Brown imagined feeding a hungry world by increasing the carbon dioxide concentration of the atmosphere to stimulate plant and biomass growth: "We have seen that plants grow more rapidly in an atmosphere that is rich in carbon dioxide. . . . If, in some manner, the carbon-dioxide content of the atmosphere could be increased threefold, world food production might be doubled" (Brown, 1954).

Within the past decade, Columbia University scientist Wallace Broecker and science writer Robert Kunzig end their book, *Fixing Climate* (Broecker and Kunzig, 2008), with a vision of future climate stabilized by CDR and carbon dioxide enhancement:

"Our children and grandchildren, having stabilized the CO₂ level at 500 or 600 ppm, may decide, consulting their history books, that it was more agreeable at 280 ppm. No doubt our more distant descendants will choose if they can to avert the next ice age; perhaps, seeing an abrupt climate

BOX 2.1 CONTINUED

change on the horizon, they will prevent it by adjusting the carbon dioxide level in the greenhouse. By then they will no longer be burning fossil fuels, so they would have to deploy some kind of carbon dioxide generator ... to operate in tandem with the carbon dioxide scrubbers."

Over the course of recent history, as knowledge of the role carbon dioxide plays in climate change has been developing, so too there have been many grand ideas about how to alter the carbon cycle (Fleming, 2010). Discussions of carbon dioxide removal in this volume are not intended to advocate any techniques for controlling the carbon cycle; rather, CDR approaches are discussed with the intent of considering options for mitigating the concentrations of CO₂ in the atmosphere that have been elevated by humans.

Proposals for CDR techniques have been put forth within the past century. Small-scale carbon dioxide removal in medical gases (anesthetics) and in closed spaces such as submarines and spacecraft has a long history, but it was in the 1930s that deforestation was understood to be one of the contributing factors to carbon dioxide buildup in the atmosphere, with reforestation implied as a valuable corrective (Callendar, 1938). Beginning in the late 1950s, direct atmospheric measurements demonstrated the natural uptake of CO₂ by the biosphere during the spring and summer in the Northern Hemisphere and the emission of CO₂ during the fall and winter (Keeling, 1960); over time, these measurements indicated that uptake by the biosphere was growing (Le Quéré et al., 2013). In the mid-1970s, Freeman Dyson suggested planting trees to remove CO₂ from the atmosphere (Dyson, 1977). This concept was later developed further by Gregg Marland (Dyson and Marland, 1979; Marland, 1988). Concerns about carbon dioxide and climate in the 1970s resulted in renewed research efforts seeking to scale up removal, reuse, and sequestration techniques to the global level. In 1976, Cesar Marchetti published a research memorandum that proposed scrubbing CO₂ from smoke stacks and injecting the stream into the Mediterranean outflow water (Marchetti, 1977). The CO₂ would then hopefully be carried into the deep Atlantic. An Oak Ridge National Laboratory report published in 1980 describes a variety of options for collecting and disposing of CO₂ (Baes et al., 1980). Another group led by Meyer Steinberg envisioned removing CO₂ from the air using a mobile nuclear reactor. In a short history of CO₂ greenhouse gas mitigation, Steinberg (1992) claims "[t]he earliest work on CO₂ mitigation was started in the U.S. by the Office of Energy Research of the U.S. Department of Energy in the 1970s." The First International Conference on Carbon Dioxide Removal, held in March 1992 in Amsterdam, represented the first major gathering of researchers in the field of CO₂ capture, disposal, and utilization (Blok et al., 1992). Also in 1992, a paper was published that suggested using plants as fuel in a bioenergy system (Marland and Marland, 1992).

TABLE 2.1 Sources and Sinks Within Earth's Carbon Cycle

		Cumulative 1750-2011 (GtCO ₂)	Average Rate 2002-2011 (GtCO ₂ /yr)
Sources	Fossil fuel combustion and cement production	1,380 ± 110	30.4 ± 2.6
	Deforestation and other land use change	660 ± 290	3.3 ± 2.9
	Total	2,040 ± 310	33.7 ± 2.9
Sinks	Atmosphere	880 ± 40	15.8 ± 0.7
	Ocean	570 ± 110	8.8 ± 2.6
	Terrestrial biosphere	590 ± 330	9.2 ± 4.8
	Total	2040 ± 310	33.7 ± 2.9
Change in atmospheric concentration		112 ± 5 ppm	2.0 ± 0.1 ppm/yr

SOURCE: IPCC, 2013a.

and the terrestrial land sink would be less effective.¹ Over a period of several decades, this would replace up to half of the CO₂ that had been removed by CDR (IPCC, 2013a). Reducing CO₂ concentration by 1 ppm/yr would require removing and sequestering CO₂ at a rate of about 18 GtCO₂/yr; reducing CO₂ concentrations by 100 ppm would require removing and sequestering a total of about 1,800 GtCO₂, or roughly the same amount of CO₂ as was added to the atmosphere from 1750 to 2000.

An additional challenge is the continued appetite of modern society for energy fueled by carbon-based sources. Efforts by developed nations to cut their emissions through conservation and increased reliance on renewable energy sources have been more than offset by growth in energy demand by developing nations, which has largely been met by fossil fuels (IPCC, 2014b). Although these supplies are fundamentally a finite resource, the fossil fuel industries have expanded exploration and improved extraction methods to allow for the production of resources previously not technically recoverable. This technical advancement has led to “reserve growth”: despite the rapid consumption of oil and natural gas, the technically recoverable reserves still in the ground during periods of technical innovation can actually increase (EIA, 2014). This phenomenon is responsible for the continued identification of large supplies of fossil fuels more than 50 years after experts predicted supplies should have peaked and been on the decline (Hubbert, 1969). Thus, dwindling supplies of fossil fuels are unlikely to be a contributor to reductions in CO₂ emissions. Energy demand, coupled with continued availability of relatively cheap fossil fuels, will only increase the need

¹ Net primary productivity would decrease with decreasing atmospheric CO₂ concentrations.

for carbon dioxide removal if atmospheric concentrations of CO₂ are going to be stabilized. The Intergovernmental Panel on Climate Change (IPCC, 2014b; Chap. 7, Table 7.2) estimates fossil fuel resources (the amount that might ultimately be recoverable using foreseeable technologies) to be in the range of 8,543 to 13,649 GtC, which would be between ~30,000 and 50,000 GtCO₂—more than 1,000 times the current annual emission rate for fossil fuel CO₂.

As noted above, CDR is defined in this report as the removal and long-term sequestration of CO₂ from the atmosphere in order to reduce global warming. There are several CDR approaches that seek to amplify the rates of processes that are already occurring as part of the natural carbon cycle, and these approaches are highlighted in Figure 2.1 along with the various processes and reservoirs that compose Earth's carbon cycle. Gross CO₂ emissions from land and the ocean are more than 20 times larger than anthropogenic emissions (Figure 2.1). Actions that enhance the reduction of these natural emissions or that increase the natural CO₂ removal from air have the potential to lower atmospheric CO₂. These strategies are variously employed in land management practices, such as low-till agriculture, reforestation (the restoration of forest on recently deforested land), and afforestation (the restoration of forest on land that has been deforested for 50 years or more); ocean iron fertilization; and land- and ocean-based accelerated weathering. These techniques are described further in Chapter 3.

In contrast to the approaches described above that seek to remove and store carbon from the atmosphere by amplifying natural processes, there are approaches that involve capturing CO₂ from the atmosphere, concentrating it, and disposing of it by pumping it underground at high pressure. One CDR approach involves the extraction of energy from biomass² through oxidation or gasification (i.e., “bioenergy”) combined with the capture and sequestration of the CO₂ generated during oxidation and gasification; this is referred to as bioenergy with carbon capture and sequestration (BECCS).³ Chemical separation methods that directly capture CO₂ from ambient air combined with long-term CO₂ disposal is referred to as direct air capture and sequestration (DACs). Traditional carbon capture and sequestration (CCS) involves the chemical separation and removal of CO₂ from power plant stack gas. Figure 2.2 com-

² Note that the growth of biomass involves the extraction of CO₂ from the atmosphere.

³ If large-scale use of fossil fuels continues, BECCS would have no advantage over using biofuels without carbon capture and sequestration (CCS) and capturing and sequestering the same amount of CO₂ from fossil fuels; the net amount of CO₂ emitted into the atmosphere would be the same. In this case, the choice of whether to add CCS to a generating plant fueled with biomass or fossil fuels should be based on economic grounds—whichever is cheaper. BECCS can, however, play a uniquely “carbon-negative” role if the amount of CO₂ that is sequestered from biomass exceeds the amount of CO₂ produced by the use of fossil fuels. See further discussion in Chapter 3.

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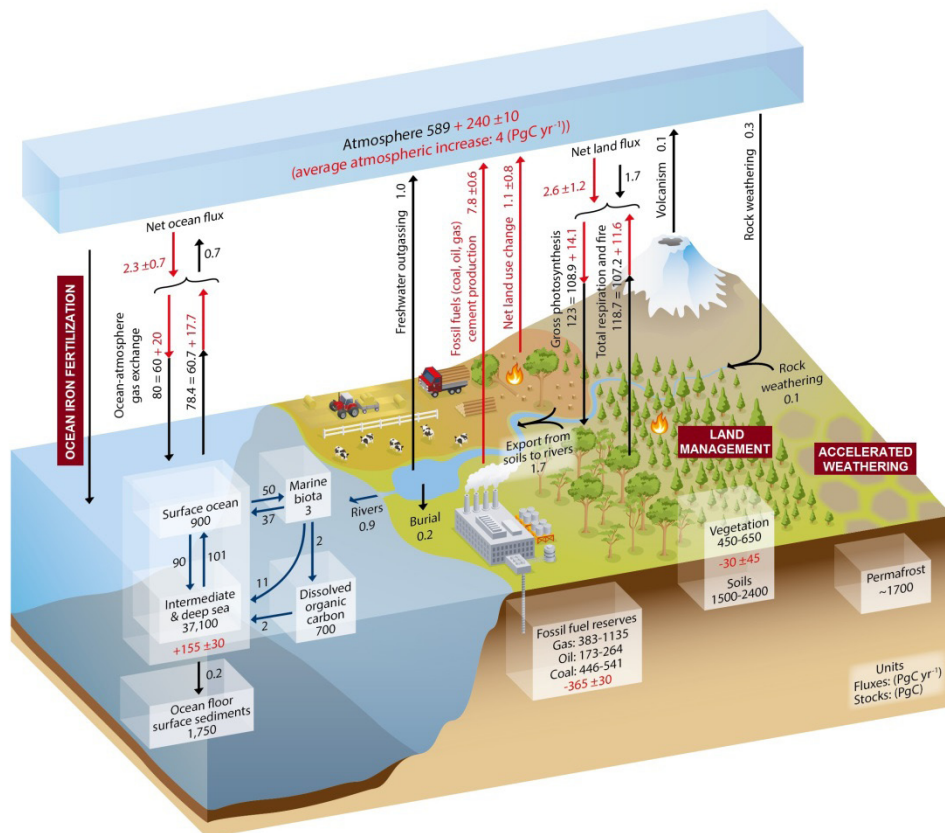


FIGURE 2.1 Simplified schematic of the global carbon cycle. Numbers represent reservoir mass, also called “carbon stocks” in PgC (1 PgC = 10^{15} gC = 3.67 GtCO₂) and annual carbon exchange fluxes (in PgC yr⁻¹). Black numbers and arrows indicate reservoir mass and exchange fluxes estimated for the time prior to the Industrial Era, about 1750. Fossil fuel reserves are from GEA (2006) and are consistent with numbers used by IPCC Working Group III for future scenarios. Red arrows and numbers indicate annual anthropogenic fluxes averaged over the 2000-2009 time period. These fluxes are a perturbation of the carbon cycle during Industrial Era post-1750. Red numbers in the reservoirs denote cumulative changes of anthropogenic carbon over the Industrial Period (1750-2011). By convention, a positive cumulative change means that a reservoir has gained carbon since 1750. Uncertainties are reported as 90 percent confidence intervals. Emission estimates and land and ocean sinks (in red) are from Table 6.1 in Section 6.3 in IPCC (2013a). For more details see IPCC (2013a).

pares BECCS, DACS, and power plant CCS approaches. These approaches are discussed individually in more detail in Chapter 3. Carbon capture and sequestration from power plants prevents CO₂ emissions but does not remove CO₂ from the atmosphere; hence, it is not considered a carbon dioxide removal approach and is not discussed in this chapter on CDR approaches.

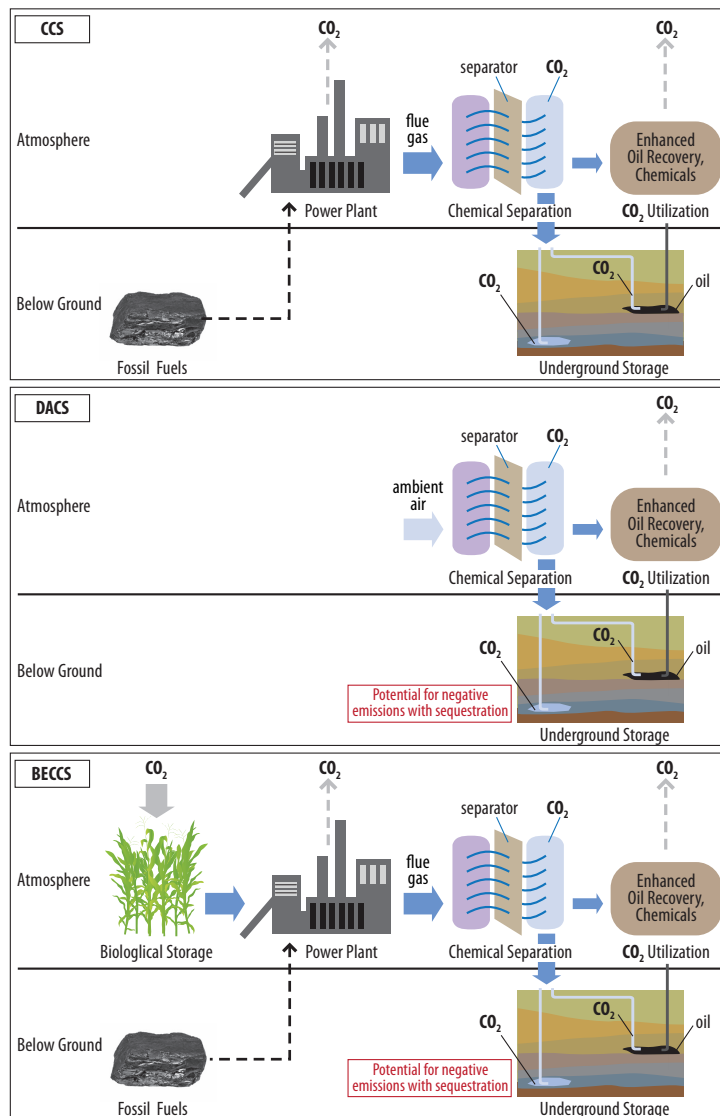


FIGURE 2.2 Comparison of components involved in several systems for carbon dioxide removal. The top panel shows the components involved in carbon capture and sequestration (CCS), the middle panel shows the components involved in direct air capture and sequestration (DACs), and the bottom panel shows the components involved in bioenergy with carbon capture and sequestration (BECCS). Block arrows show fluxes of carbon (as fuel or as CO₂); dashed arrows indicate residual CO₂ emissions. BECCS and DACs are carbon-negative approaches if some or all of the captured CO₂ goes into geological sequestration, whereas CCS is at best a carbon-neutral process. The utilization of CO₂ for enhanced oil recovery and other uses is discussed in Chapter 3, as are capture and sequestration methods that incorporate CO₂ into solid or liquid materials.

Assessing the potential benefit offered by different CDR methods involves estimating feasible rates of atmospheric CO₂ removal in addition to a given method's total CO₂ reduction capacity over timescales of interest (i.e., up to 2100). A more thorough assessment that could inform prioritization of future research and development efforts would in addition assess risks, costs, and efficacy, as well as the potential for research and development to reduce barriers to widespread deployment. Table 2.2 shows a preliminary comparison of the potential impacts, costs, and limitations associated with each of the CDR methods of focus in this report. The preliminary judgments shown in Table 2.2 could be affected by new information that could be produced, for example, by additional research. A comparison to current and projected emissions places these estimates in context. Note that these CDR approaches are discussed in greater detail in Chapter 3.

TABLE 2.2 Summary of the Potential Impacts of Various CDR Strategies

CDR Method	Rate of Capture or Cumulative Sequestration		Cost [\$/tCO ₂]	Limitations	
	[GtCO ₂ /yr]	CDR to 2100 [GtCO ₂]			
Land management Afforestation/ Reforestation	2-5 ^a	100 ^b	1-100 ^c	<ul style="list-style-type: none"> • Irreversible land changes from deforestation or past land uses • Decreased biodiversity • Competition for land for agricultural production 	
	Accelerated weathering Land	2 (U.S. only)	~100 (U.S. only)	<ul style="list-style-type: none"> • Land—available cheap alkalinity and aggregate markets for product • Ocean—available cheap alkalinity 	
	Ocean	1 ^d	~100	50-100 ^f	
Combined Capture and Sequestration	Ocean iron fertilization	1-4 ^g	90-300	500 ^h	<ul style="list-style-type: none"> • Environmental consequences and potential co-benefits • Uncertainty in net carbon sequestration
	Bioenergy with capture (Theoretical)	15-18 ⁱ	100-1,000 ^j	~100 ^k	<ul style="list-style-type: none"> • Sequestration of 18 GtCO₂/yr requires ~1,000 million acres of arable land (1,530 million acres available worldwide; actual amount of arable land available for bioenergy production will likely be significantly less because much of arable land area is required for food production)
Capture	Direct air capture (U.S. only)	10 ^m	~1,000 (U.S. only)	400-1,000 ⁿ	<ul style="list-style-type: none"> • Land available for solar ~100,000,000 acres of BLM land in southwestern United States^o

continued

TABLE 2.2 Continued

CDR Method	Rate of Capture or Sequestration		Cumulative CDR to 2100 [GtCO ₂]	Cost [\$/tCO ₂]	Limitations
	[GtCO ₂ /yr]	[GtCO ₂ /yr]			
Geologic	1–20 ^p (2DS)	800 ^q (2DS)	2,000–10,000 ^r	10–20 ^q	<ul style="list-style-type: none"> Permeability of formation, number of wells, and overall size of the sequestration reservoir
Ocean (molecular CO ₂)	?	?	2,000–10,000 ^r	10–20 ^r	<ul style="list-style-type: none"> Environmental consequences associated with ocean acidification
Ocean (CO ₂ neutralized with added alkalinity)	?	?	?	10–100 ^r	<ul style="list-style-type: none"> Availability of alkaline minerals

NOTE: Amounts of CO₂ included in table are estimates of the theoretical or potentially feasible amounts, with the exception of those noted as the amounts required to keep global warming to less than 2°C (2DS). These estimates are provided mostly to only one significant figure to indicate possible scales of deployment and costs as estimated in published literature. Real-world values could differ substantially from these estimates.

^a Smith and Torn, 2013; Lenton, 2010. ^b Nilsson and Schopfhauser, 1995; Lenton, 2010. ^c Richards and Stokes, 2004; Stavins and Richards, 2005; IPCC, 2014b. ^d Kirchofer et al., 2012; McLaren, 2012; Rau et al., 2013. ^e Assuming ~4.65 GJ/tCO₂ for the case of mineral carbonation via olivine at 155°C and electric energy source from coal (Kirchofer et al., 2012); ocean-land requirement of < 7 × 10⁵ km²/GtCO₂ captured per year, assuming wind as energy resource. ^f IPCC, 2014a; McLaren, 2012; Rau et al., 2013. ^g Aumont and Bopp, 2006. ^h Harrison, 2013. ⁱ Krieglner et al., 2013; Azar et al., 2010. ^j Lenton, 2010; Lenton and Vaughan, 2009; Krieglner et al., 2013. ^k Assuming similar costs to carbon capture at a conventional coal-fired power plant (Rubin and Zhai, 2012). ^l Alexandratos and Bruinsma, 2012. ^m If fueled from solar, assuming an estimate of ~11 acres per MW electricity used for powering direct air capture (DAC), and based on the range of energy requirement estimates in the literature, ~31,000 acres required to remove emissions associated with one 500-MW power plant (i.e., 11,000 tCO₂/day); note that the single DAC plant to offset emissions of the 500-MW power plant is only 33 acres. ⁿ Mazzotti et al., 2013; House et al., 2011. ^o Bureau of Land Management, 2012. ^p Assuming increasing rate of sequestration: 1 GtCO₂/yr in 2025, 7.5 GtCO₂/yr in 2050, and 19 GtCO₂/yr in 2100, which is based on required projections to limit total global warming to 2°C (IEA, 2013b) and gives a total amount sequestered of 800 GtCO₂. ^q NETL, 2013; ITFCCS, 2010. ^r Maximum capacity in equilibrium with atmospheres ranging from 350 to 1,000 ppm (IPCC, 2005). ^s No specific upper bounds appear in the literature, but maximum rates of deployment this century are likely to be limited by economic and/or local environmental concerns and not any fundamental physical barriers.

Assessment of Possible Carbon Dioxide Removal and Long-Term Sequestration Systems

This chapter reviews a number of systems to remove carbon dioxide from the atmosphere and reliably store it for long periods of time. Several techniques that integrate carbon capture and sequestration as a single inseparable process are described first: land management strategies, accelerated weathering on land and in the ocean, and ocean iron fertilization. This is followed by a discussion of two methods in which capture and disposal are separate: bioenergy with carbon capture and sequestration (BECCS) and direct air capture and sequestration (DACs). A table summarizing a number of aspects of these systems is presented at the end of this chapter. Other approaches have been suggested; however, the committee focuses here on techniques for which there is sufficient information to make a preliminary assessment.

LAND MANAGEMENT

Afforestation and Reforestation

Currently, global reforestation (the restoration of forest on recently deforested land) and afforestation (the restoration of forest on land that has been deforested for 50 years or more) create substantial carbon sinks, with net annual uptake of about 1 GtCO₂ (Baumert et al., 2005). Deforestation, on the other hand, is the single largest source of land use-related greenhouse gas (GHG) emissions and accounts for about 10 percent of total current anthropogenic GHG emissions from all sources (and one-third of total cumulative emissions from all sources). As shown in Table 2.1, net land use emissions averaged 3.3 ± 2.9 GtCO₂/yr between 2002 and 2011 and were dominated by tropical deforestation. Land use emissions since 1750 total about 660 GtCO₂, which suggests an upper limit to the physical potential of reforestation and afforestation to remove carbon dioxide from the atmosphere. In reality, the number would be much lower because society needs to manage previously forested land to meet the need for food and fiber, and these managed systems typically have lower average carbon stocks than they did prior to conversion.

Until the early twentieth century, the highest rates of deforestation occurred in temperate forests in Asia, Europe, and North America. However, deforestation had essentially stopped in the world's temperate forests by midcentury. As deforestation slowed in the temperate zone, it increased rapidly in the world's tropical forests (FAO, 2010). Rates of deforestation in boreal forests tend to be lower than in tropical forests (Ruckstuhl et al., 2008). A critical component of any climate mitigation strategy is to prevent additional tropical deforestation, which as an outside limit could add as much as 1,800 GtCO₂ to the atmosphere in cumulative emissions—roughly as much CO₂ as from all the fossil fuel use from the preindustrial period until the present (Allen et al., 2009). Emissions from deforestation and land use change are about one-tenth of those from fossil fuels and cement production (see Table 2.1).

The rate at which carbon can be removed from the atmosphere through afforestation and reforestation is determined by a number of factors, including the age of trees, species composition, temperature, geology, precipitation, carbon dioxide concentration, and site history. The Intergovernmental Panel on Climate Change (IPCC) report, *Land Use, Land-Use Change, and Forestry* (IPCC, 2000), provides average annual net uptake rates associated with afforestation and reforestation activities of 1.5-4.5, 5.5-16, and 15-30 tCO₂/ha for boreal, temperate, and tropical forests, respectively. The rate of net uptake typically reaches a maximum in 30-40 years, although the timing depends on biome type and site factors. After this initial phase, the rate of net uptake declines to zero as the forest matures, with the timing depending on forest type and structure (Ryan et al., 1997).

The IPCC Fifth Assessment reports potential carbon sequestration rates of up to 1.5, 9.5, and 14 GtCO₂/yr in 2030 for global afforestation and reforestation activities, depending on the mitigation scenario (IPCC, 2014b, Table 11.8); these estimates are slightly higher than other estimates because they include CH₄ and N₂O in addition to CO₂. Brown et al. (1996) estimated a maximum physical potential carbon sequestration rate of 4-6 GtCO₂/yr for global afforestation and reforestation activities. Smith and Torn (2013) estimate that removing 3.7 GtCO₂/yr through tropical afforestation would require at least 7 Mha/yr of land,¹ 0.09 Mt/yr of nitrogen, and 0.2 Mt/yr of phosphorus and would result in a 50 percent increase in evapotranspiration from this land; this is a better estimate of a feasible maximum rate of CO₂ removal compared to earlier higher estimates. Nitrogen required for both BECCS (discussed below) and afforestation raises an additional concern: 1 percent to 5 percent of nitrogen fertilizer is converted to nitrous oxide, which has a global warming potential up to 300 times greater than CO₂ (Crutzen et al., 2008; IPCC, 2013b). In one example in which this was further quantified,

¹ For reference, the state of West Virginia has a total area of 6.3 Mha (U.S. Census Bureau, 2012).

the addition of inorganic fertilizer with subsequent N_2O emissions can offset stored CO_2 by 75 percent to 310 percent (Brown et al., 2004; Li et al., 2005; Robertson et al., 2000).

There are natural limits to the amount of carbon that can be removed from the atmosphere through reforestation and afforestation. When a forest ecosystem matures, the rate of CO_2 uptake is balanced by respiration and the decay of dead organic matter. Based on land availability over the next 100 years, afforestation has been estimated to have a physical potential cumulative global impact of about 380 Gt CO_2 (Nilsson and Schopfhauser, 1995). Based on past soil carbon losses and the availability of land over the next 50 years, physical potential soil carbon sequestration estimates are between 110 and 180 Gt CO_2 (Lal, 2004).

Excluding deforestation, terrestrial ecosystems currently sequester carbon on a global scale, largely as a result of forest regrowth on lands previously cleared for agricultural use in the Northern Hemisphere and enhanced productivity in response to increasing carbon dioxide concentrations. It is unclear, however, how a changing climate will affect sequestration. If climate change results in widespread forest disease or accelerates the decomposition of carbon stored in soils, terrestrial ecosystems could become a net source rather than a sink of GHGs, further contributing to climate change (USGS, 2011, 2012). However, if climate or land use-induced transitions are more gradual, shifts in carbon stocks may not be large, even in the presence of major species shifts. The spatial scale of any accelerated disturbance regimes (e.g., fire, exotic pests and pathogens, or extreme weather) will determine if rapid loss of sequestered carbon is likely (USGS, 2011, 2012). Either way, the rate of additional sequestration of carbon in terrestrial ecosystems in the Northern Hemisphere will decline as afforested trees mature or are brought under management. Increasing atmospheric CO_2 content also affects carbon sequestration. If CO_2 fertilization of plants proves to have a substantial effect on carbon sequestration in forests, higher future CO_2 concentrations may act to increase the effectiveness of afforestation and reforestation (Bala et al., 2007).

Biological sequestration in forests can be relatively inexpensive. In the United States, the cost of a program of 1.1 Gt CO_2 /yr of forest sequestration has been estimated at \$7.5/t CO_2 to \$22/t CO_2 (Stavins and Richards, 2005), and at higher volumes of sequestration, the cost per ton is comparable to other abatement techniques. Another review of forest mitigation opportunities in the United States found that carbon prices from \$1/t CO_2 to \$41/t CO_2 generated an economic mitigation potential of 0.5 to 2.7 Gt CO_2 in total forest carbon (Richards and Stokes, 2004). A study by the U.S. Environmental Protection Agency (USEPA, 2005) suggested that, at \$15/t CO_2 , the mitigation potential of afforestation and forest management in the United States would amount to

0.35 GtCO₂/yr over a 100-year time frame. The IPCC Fifth Assessment reports potential carbon sequestration for global afforestation and reforestation activities at costs between \$20/tCO₂ and \$100/tCO₂, depending on the scale of the activity (IPCC, 2014b, Table 11.8). A major question is whether the true cost of preserving the forest for millennia is accounted for in the cost estimates, and whether the appropriate liabilities for accidental or intentional release of carbon by fire or future harvesting have been factored into the costs.

Although reforestation and afforestation projects remove CO₂ from the atmosphere that would otherwise contribute to global climate change, the net climatic impact of additional forest growth is determined by the combination of carbon-cycle impacts with biogeophysical processes including albedo and hydrological impacts, which are coupled through cloud feedbacks, sensible and latent heat fluxes, and water vapor (Anderson et al., 2011; Bala et al., 2007; Bonan, 2008; Swann et al., 2010, 2012). In tropical forests, increases in tree growth may lead to an increase in evapotranspiration that can warm the atmosphere through the greenhouse effect but cool the atmosphere through enhanced cloudiness and albedo, as well as cool the land surface directly through evaporation. In boreal regions, planting trees on open land that is often covered by snow in wintertime decreases surface albedo, resulting in surface warming (Bonan, 2008). The net climatic effect of additional temperate and high-latitude forest sequestration is unclear. Model simulations by Swann et al. (2010) suggest that an increase in atmospheric water vapor from the growth of high-latitude deciduous forests in the future will have a warming effect 1.5 times larger than that due to changes in surface albedo, offsetting the impact of carbon uptake.

In the near term, the benefits of reducing deforestation are greater than that of reforestation and afforestation. In a study of seven developing countries, half of the cumulative mitigation potential of 23 GtCO₂ between 2000 and 2030 could be achieved at a negative cost (Sathaye et al., 2001). Slowing or even ending deforestation is a CO₂ mitigation strategy, but it is not considered carbon dioxide removal (CDR) since it does not result in a net decrease in atmospheric CO₂.

Carbon Sequestration on Agricultural Lands

The use of land for agricultural production has led to a net transfer of terrestrial carbon to the atmosphere. It is estimated that, over the past 10,000 years, land conversion and land use caused soil carbon to decrease globally by 840 GtCO₂ (Lal, 2001). On average, the amount of organic carbon in intensively cultivated soils is much lower than the potential carbon sequestration capacity below ground. Many cultivated soils have

lost 50 to 70 percent of their original organic carbon (IPCC, 2000), and that intensive soil cultivation has the potential to reduce soil carbon by 25 percent to 50 percent after 30-50 years (Johnson, 1992; Post and Kwon, 2000; Wei et al., 2014). Although it is difficult to compensate for the conversion of forests to cultivated lands, in part because most of the carbon in forest ecosystems is above ground, it is possible to manage agricultural lands to partially reverse the loss of carbon in some situations (Lal, 2007). Soil carbon can be increased by growing cover crops,² leaving crop residues to decay in the field, applying manure or compost, using low- or no-till systems, and employing other land management techniques that increase soil structure and organic matter inputs.

Cover crops can be grown when a field is not planted with a market crop; they can increase organic matter inputs into the soil and have been found to increase soil carbon sequestration (Freibauer et al., 2004). Cover crops are also reported to decrease emissions of nitrous oxide and leaching losses of soil nitrate in some situations. In Iowa, double cropping, in which a food or feed crop such as maize is grown during its usual growing season, and a second crop is grown as an energy source at other times, was found to offer similar carbon benefits as the use of a conventionally managed sole-crop system while also producing 20 percent more dry biomass for bioenergy (Heggenstaller et al., 2008). The mitigation potential for this type of improved agronomy practice has been estimated to have a range of 0.07 to 0.7 tCO₂-eq/yr per hectare, with significantly higher values in warm and moist climates (Smith et al., 2007). Such efforts could be sustained for a decade or so before uptake rates would level off as soil carbon content approached steady state.

Most farmers, both in the United States and globally, plow fields before planting, which increases decomposition rates through the “priming effect” with the net effect of releasing carbon from the soil into the atmosphere until a lower equilibrium is established. Switching to no- or low-till practices has the potential for increased carbon sequestration in soil. Marland et al. (2003) conclude that, for the average U.S. farm, a change from conventional tillage to no-till agriculture will result in net soil carbon sequestration that averages 1.2 tCO₂/yr per hectare for the first 20 years with a decline to near zero in the following decades. More recent analyses suggest that no-till agriculture results in some net sequestration of soil carbon, but the amount of carbon stored is much smaller (about a 5 percent increase in soil carbon) and less consistent than previously believed (Baker et al., 2007). Another important point is that the benefits of no-till agriculture may be reversed by reintroducing tilling. Thus, for no-till practices to

² Often leguminous crops such as bean, lentil, and alfalfa (Thiessen-Martens et al., 2005).

be used effectively as a form of long-term carbon sequestration, the practice must be maintained without interruption.

The greatest per-hectare emissions of CO₂ from agricultural soils have occurred on cropland created by the drainage of wetlands and the lowering of water tables by installation of drainage systems often referred to as “tiling” (Fargione et al., 2008). Prior to cultivation, these lands were rich in organic carbon due to anoxic conditions in hydric soils. Both draining and tiling allow oxygen to enter deeper into these soils, greatly increasing the rate at which organic matter is decomposed to carbon dioxide. Smith et al. (2008) note that raising water tables and converting cropland back to wetlands can lead to “rapid accumulation of soil carbon” but may also increase releases of methane, a potent GHG. The mitigation potential of improved water management activities is estimated to be between -0.6 and 3 tCO₂-eq/yr per hectare (Smith et al., 2007).

Although intensively managed annual croplands lose much of their pre-agricultural soil carbon, well-managed pastures retain most of their soil carbon (Guo and Gifford, 2002). The rate at which soil carbon increases in former croplands is reported to be greater when they are planted with diverse mixtures of both grass and legume species (Guo and Gifford, 2002; Tilman et al., 2006). Over a 10-year period, a low-input, high-diversity bioenergy crop grown on low-nutrient-status agricultural soils had a total sequestration rate of 4.4 tCO₂/yr per hectare in soil and roots, although the research suggests that this rate might decline to 3.3 tCO₂/yr per hectare with time because of slower root mass accumulation (Tilman et al., 2006). This is contrasted with a lack of carbon accumulation in previously agriculturally disturbed soils in New England with up to 120 years of reforestation (Compton and Boone, 2000). Programs that set aside agricultural land can increase net carbon sequestration and provide wetland, stream, river, and lake protection, although indirect land use impacts (i.e., the creation of farmland in other regions or countries to offset the land set aside) should be considered (Plevin et al., 2010).

Most of the estimates in this section are on a per-hectare basis. Of the total 13 billion hectares that make up Earth’s ice-free surface, cropland accounts for ~12 percent, pastureland ~26 percent, forest land ~32 percent, and urban land ~9 percent (Foley et al., 2011). The global technical potential for agricultural land management is 5.2 GtCO₂/yr in 2030 (IPCC, 2014b). The carbon removal potential of these techniques will need to be balanced with food production needs and other co-benefits and side effects will need to be factored in. This is also true for biochar, which is another technique for affixing carbon (Box 3.1).

Another possible method of enhancing carbon sequestration is to store biomass, such as crop or forest residues, in the ocean. As described by Strand and Benford (2009) and

BOX 3.1 BIOCHAR

Biochar refers to a broad class of products in which biomass (e.g., trees, grasses, and crop residuals) is combusted at moderately low temperatures (300°C to 600°C) without oxygen through low-temperature pyrolysis. The pyrolysis process allows for the formation of charcoal, a relatively stable form of organic carbon, thereby slowing the inevitable release of CO₂ into the atmosphere due to decomposition when compared with adding the organic matter to the soil directly. The residence time of biochar in situ is not well established (Gurwick et al., 2013). Although there has been research associated with the role biochar could play in carbon and nitrogen dynamics, the literature is still limited, and the impacts of utilization on net greenhouse gas emissions are not well defined (Gurwick et al., 2013). Since biochar is seen as largely responsible for reducing emissions by decreasing decomposition of waste plant material through the potential long-term sequestration of the carbon in the soil, it is not classified in the current work as a CDR technology. Further complicating consideration of biochar as a CDR technology is the fact that pyrolysis produces less net useable energy per unit of carbon emitted to the atmosphere than does combustion of the same material (Gaunt and Lehmann, 2008). Additionally, changing the temperature and speed of the pyrolysis process can influence the mechanism by which the char forms and the stability of the resulting char (Milosavljevic et al., 1996).

Combusting waste biomass to produce energy would displace more fossil fuel and reduce net greenhouse gas emissions to a greater degree than using that material as a feedstock for biochar production. If fossil fuel use has been eliminated in the area where the biomass is produced and energy needs are not being fully met, then combusting waste material to produce bio-energy would produce lower net greenhouse gas emissions than would production of biochar. If additional energy is not needed to meet human needs, then biochar production will reduce net greenhouse gas emissions relative to allowing that waste to decompose. If the deployment of biochar requires additional mixing of the soil, the priming effect discussed previously with regards to no-till agriculture will result in increased oxidation of organic material in the soil and a concomitant increase in carbon dioxide emissions over the short to medium term. Despite not being among the CDR approaches, biochar does have benefits to agricultural practices such as improving soil structure (water and fertilizer retention), removing contaminants, and enhancing fertility in degraded soils.

Metzger and Benford (2001), by packaging and sinking land biomass into the deep ocean, especially in areas low in oxygen, the normal return of this carbon via decomposition and respiration is greatly impeded if not eliminated.

Summary of Land Management Approaches

Looking forward, there are several important future research directions that deserve consideration, together with their potential for negative ecological impacts:

- Systems analysis to develop strategies for afforestation and reforestation efforts alongside biomass and food production with minimal competition for land and maximum CDR potential;
- Development of technologies for advanced ammonia fertilizer production with lower energy requirements and related CO₂ emissions (it is important to note that increased nitrogen application can result in higher rates of denitrification and N₂O production, a potent greenhouse gas); and
- Engineering plant varieties that are better able to remove carbon dioxide and reliably store it for extended periods, for example, by developing plants that achieve higher photosynthetic rates than native vegetation under extreme conditions (e.g., minimal water, “nonarable” land) to limit competition with food and/or biomass production.

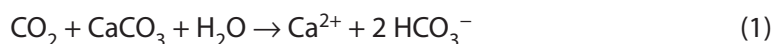
In summary, land management approaches—reforestation, afforestation, and changed management practices for agricultural lands—are mature technologies that are readily deployable with well-known environmental consequences. In total, they have the potential to remove significant but limited amounts of CO₂ from the atmosphere (i.e., ~380 GtCO₂ total out to the year 2100 at a maximum rate of between 2 and 5 GtCO₂/yr for afforestation and reforestation), with a comparable potential sequestration rate from changed agricultural practices. The costs for afforestation and reforestation are generally low compared to other CDR techniques, that is, approximately \$1/tCO₂ to \$100/tCO₂ (IPCC, 2014b; Richards and Stokes, 2004; Stavins and Richards, 2005). The maximum potential for total CO₂ removal from the atmosphere is on the order of the total amount that has been removed from terrestrial ecosystems by human activities—roughly 660 GtCO₂, equivalent to a reduction of 40–70 ppm in atmospheric CO₂ concentration by 2100 (House et al., 2002). Implementation of these techniques is unlikely to achieve anything close to this maximum potential due to the increasing demands for agricultural production and the difficulty of reaccumulating carbon on depleted landscapes. Though these techniques are clearly not a solution by themselves, they can be valuable elements of a climate change mitigation portfolio.

ACCELERATED WEATHERING METHODS AND MINERAL CARBONATION

The long-term fate for most CO₂ released to the atmosphere is first to become bicarbonate ions dissolved in the ocean and later to become carbonate sediments on the sea floor (Bernier et al., 1983). These transformations occur as a result of ions provided by carbonate and silicate weathering reactions that typically occur in soils or marine sediments. One class of CDR involves accelerating these carbonate and/or silicate weathering reactions so that CO₂ may be stored in the ocean predominately in the

form of bicarbonate ions or stored in the ocean or on land in the form of a calcium carbonate solid (Dunsmore, 1992; Geerlings and Zevenhoven, 2013; Hartmann et al., 2013; Lackner, 2002, 2003; Olajire, 2013; Sanna et al., 2014; Stephens and Keith, 2008).³ In principal, these weathering reactions could be accelerated by bringing high CO₂ concentrations in contact with appropriate naturally occurring rock formations, creating carbonate minerals in situ. Alternatively, they could be accelerated by transporting the appropriate minerals for processing in an industrial setting. Last, the appropriate minerals could be ground up, transported, and released into the ocean.

Carbon dioxide released into the atmosphere exchanges with carbon in the land biosphere and ocean on timescales ranging from seconds to millennia. However, as seawater absorbs CO₂ from the atmosphere, it becomes more acidic, and this inhibits further absorption. The dissolution of calcium carbonate minerals either on land or in the ocean neutralizes some of this acidity and thus allows the seawater to absorb more CO₂ (Archer et al., 2009); CO₂ in addition to calcium carbonate (CaCO₃) and water yields calcium ions (Ca²⁺) and bicarbonate ions (HCO₃⁻) in solution:

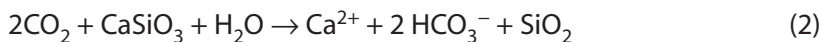


When added to the ocean, the dissolved calcium and bicarbonate ions increase the alkalinity of seawater. It typically takes 2,000 to 8,000 years for reaction (1) to return the ocean-surface sediment carbonate system naturally to steady state following a perturbation such as the release of carbon dioxide into the atmosphere. (Equilibration with both the silicate and carbonate mineral cycles takes much longer, on the order of hundreds of thousands of years.) The long timescale associated with carbonate sediment equilibration arises in part because of slow ocean transport of dissolved carbon dioxide and because of the rates of the natural calcium carbonate cycle that involves weathering on land and deposition in marine sediments (Archer et al., 2009). Thus, one set of concepts involves strategies to accelerate the weathering reaction [Eq. (1)] (Harvey, 2008; Rau, 2011; Rau and Caldeira, 1999). The basic idea of these proposed strategies is that—if CO₂ additions are going to eventually dissolve calcium carbonate minerals in the ocean and in so doing reduce both the atmospheric load of CO₂ and the amount of ocean acidification caused by the CO₂—it should be possible to accelerate carbonate dissolution reactions so as to achieve these perceived benefits more rapidly.

Silicate weathering reactions can also affect marine chemistry in a way similar to dissolution of carbonate minerals. However, because silicate minerals do not in general

³In the discussion here, for simplicity, the committee discusses calcium with the understanding that other divalent cations, such as magnesium, are also possible.

contain carbon, twice as much carbon can usually be stored in the ocean from weathering reactions with silicate minerals as compared with carbonate minerals per mole; that is, two moles of CO_2 react with one mole of calcium silicate mineral (CaSiO_3) and water, yielding calcium ions and bicarbonate ions in solution plus silica (SiO_2):



In nature, it typically takes hundreds of thousands of years for reaction (2) to return the ocean-surface sediment silicate system to steady state (Caldeira and Rampino, 1990), but various strategies have been proposed to accelerate this reaction (Köhler et al., 2010, 2013; Schuiling and de Boer, 2011; Schuiling and Krijgsman, 2006).

The long-term fate for most CO_2 released into the atmosphere is to become carbonate sediments in the ocean, where the cations in the carbonate minerals are derived from silicate-mineral weathering reactions. Schematically, this reaction,⁴ in which CO_2 reacts with a silicate mineral to become a carbonate mineral plus silica, may be written as



Reaction (3) can form a solid carbonate. Note, however, that in this simplified representation, twice as much CO_2 can be removed from the atmosphere if the resulting solution is allowed to be disposed of in the ocean [reaction (2)] relative to what would occur were a solid to be formed [reaction (3)] and disposed of directly as a solid.

All three of these weathering reactions, (1), (2), and (3), have been discussed as the basis for possible mechanisms for removing CO_2 from the atmosphere at a large scale. It should be noted that there are no “silver bullets” in any of these accelerated weathering approaches. In reaction (1), the amount of calcium carbonate mass required is 2.3 times as large as the mass of CO_2 removed.⁵ Similarly, for reactions (2) and (3), the silicate mineral mass must exceed the CO_2 mass by a factor of 1.3 or 2.6, respectively, and for reaction (3), the mass of the resulting solids (calcium carbonate plus silica) will exceed the mass of CO_2 by a factor of 3.6.⁶ The use of other silicate minerals, such as olivine, can potentially improve these ratios, but deployed at scale, all of these methods would involve mining of substantial masses of mineral—on the order 100 billion tons/yr to offset current CO_2 emissions ($\sim 34 \text{ GtCO}_2/\text{yr}$; see Table 2.1). For comparison, U.S. production of crushed stone or coal is about 1 billion tons/yr, and total world production of coal is about 8 billion tons/yr (USGS, 2013a). If the atmospheric CO_2 is to

⁴These reactions should be interpreted as simplified archetypes of reactions as reactions actually used may be considerably more complicated.

⁵ CaCO_3 is 100 g/mole and CO_2 is 44 g/mole.

⁶ For reaction (2) 116 g of CaSiO_3 would be needed for each 88 g of CO_2 ; for reaction (3), 116 g of CaSiO_3 would be needed for each 44 g of CO_2 and would produce 100 g of CaCO_3 and 60 g of SiO_2 .

be stored in the form of a solid carbonate mineral (e.g., CaCO_3), then simple examination of the elemental composition indicates that the mass of the minerals to be stored must be at least ~ 2.3 times the mass of the CO_2 . If year 2013 CO_2 emissions ($\sim 36 \text{ GtCO}_2$; Le Quéré et al., 2014) were entirely stored in the form of CaCO_3 , this would represent over 80 billion tons of carbonate mineral. Transport and disposal of a substantial fraction of this mass could pose formidable challenges. Furthermore, many weathering reactions are favored in relatively dilute solutions, so the volumes of water needed could in some cases be substantial (Rau and Caldeira, 1999), although not all approaches require the movement of water (Harvey, 2008; Kheshgi, 1995; Köhler et al., 2013).

Reactions similar to those listed above have been discussed in the context of carbon capture from large point sources of CO_2 , such as electricity generation or cement manufacturing facilities (IPCC, 2005). Examples of proposals to use accelerated mineral weathering approaches at such large point sources can be found in a wide range of sources (Béarat et al., 2006; Chizmeshya et al., 2007; Gerdemann et al., 2007; House et al., 2007; Kirchofer et al., 2012; O'Connor et al., 2004; Park and Fan, 2004; Park et al., 2003; Rau, 2011). Under the definitions used in the current work, carbon sequestration from such point sources would be considered “climate engineering” if the CDR was associated with BECCS or DACS. Such facilities at scale would require substantial amounts of mass handling. For example, Rau and Caldeira (1999) and Rau (2011) estimate that about 5,000 to 10,000 tons of water would need to be pumped for each ton of CO_2 stored. Thus, these approaches favor coastally located facilities where there is ready access to seawater.

Another approach is to encourage carbonate or silicate mineral weathering reactions to occur on land (Köhler et al., 2010; Schuiling and Krijgsman, 2006) or in the ocean (Harvey, 2008; Köhler et al., 2013; Schuiling and de Boer, 2011) rather than in a centralized facility. These approaches involve crushing and distributing minerals over a broad area so that chemical weathering reactions may be accelerated by generating high amounts of reactive surface area. Such approaches involve substantial amounts of transportation and distribution of materials to have a substantial climate effect (Hangx and Spiers, 2009). An important issue is that the near-surface ocean is saturated with respect to most carbonate minerals, and the kinetics of silicate mineral dissolution are usually slow. Kheshgi (1995) suggests that by being more selective in the materials mined, or by preprocessing the mined minerals to create more soluble chemicals, compounds can be added to the near-surface ocean that would dissolve and therefore cause the ocean to take up more carbon dioxide from the atmosphere. Harvey (2008) suggests that these goals could be achieved by sinking a fine carbonate mineral powder from the surface ocean with the aim of dissolving it in undersaturated waters below. Schuiling and Krijgsman (2006) suggest silicate mineral reaction rates

could be accelerated by grinding minerals finely and then spreading them on farmlands or forests, or in the coastal ocean. A variety of electrochemical approaches to accelerating mineral weathering have also been proposed, although required electricity inputs would be substantial (House et al., 2007; Rau, 2008; Rau et al., 2013).

The approaches described above focus on bringing carbonate or silicate minerals to locations where they may react with carbon dioxide. Another strategy is to bring carbon dioxide to where it may react in situ with naturally occurring minerals. Natural uptake of CO₂ by olivine has been documented in Oman (Kelemen et al., 2011; Matter and Kelemen, 2009). These studies indicate the need for improved understanding of fundamental CO₂-reaction fluid-mineral interactions for mineral carbonation (Gadikota and Park, 2014; Gadikota et al., 2014a,b), which would also be relevant for understanding the fate of CO₂ once it is injected into geologic formations containing silicate minerals.

As previously noted, accelerated chemical weathering approaches typically aim to dispose of (store) carbon in one of two forms, either as a solid carbonate mineral or as dissolved bicarbonate in the ocean. A seawater solution containing dissolved CO₂ accompanied by added alkalinity (i.e., increasing Ca²⁺) stores nearly twice as much CO₂ per unit of mineral dissolved; however, use of the ocean raises a range of legal and ethical issues (discussed in Chapter 4).

Scaling and Environmental Issues

Carbonate minerals, silicate minerals, and seawater are all abundant and so there are no obvious fundamental physical constraints that limit the application of these approaches at the global scale. Indeed, carbonate and silicate weathering reactions will be the way that nature slowly and eventually removes anthropogenic CO₂ from Earth's exchangeable surface reservoirs over thousands to hundreds of thousands of years. However, there are substantial real-world constraints that suggest a limited role for markedly accelerating these weathering reactions. First, as noted previously, widespread application of these approaches would require a substantial scale-up of carbonate or silicate mining, and some approaches require the use of large volumes of seawater. For many of these proposals, the large material requirements involved likely limit economically foreseeable applications to locations where appropriate minerals are coastally located.

Beyond the effects of mining and transporting so much mineral material, there are a range of environmental concerns associated with the use of the ocean. For point-source applications, there are concerns about environmental damage resulting from

the intake of large volumes of water. Depending on the ratio of CO₂ to alkalinity added to the seawater, there is a potential for these approaches to increase ocean pH and carbonate mineral saturation and thereby to counter some adverse environmental effects of ocean acidification. To have substantial effects on ocean carbonate chemistry at a global scale would involve mining and crushing hundreds of cubic kilometers of carbonate and/or silicate minerals. For comparison, in 2011, worldwide coal production was equivalent to about 9 km³ (USGS, 2013a); associated mineral mass movement is likely to have been several times greater. There is also some concern about environmental consequences of adding CO₂-rich alkaline fluids to the ocean. Although there is no evidence of deleterious effects of adding alkalinity to waters that have been acidified as a result of excess CO₂, adding alkalinity to seawater does not remove the excess CO₂ and so is not going to restore the status quo; thus, there is potential for unanticipated ecological consequences.

Looking at the entire process of possible accelerated weathering CDR strategies, a recent study carried out by Kirchofer et al. (2012) investigated the impact of alkalinity source on the life-cycle energy efficiency of mineral carbonation technologies; see Figure 3.1. The life-cycle analysis (LCA) of aqueous mineral carbonation suggests that a variety of natural and industrial byproduct-based alkalinity sources and process configurations have the potential to achieve net CO₂ reductions. Natural silicate minerals (e.g., olivine and serpentine) were chosen due to their environmental abundance and widespread global availability (Krevor et al., 2009). Due to the slow kinetics of silicate dissolution in addition to the mining and grinding efforts associated with natural alkalinity sources, industrial byproducts (i.e., fly ash, cement kiln dust, and iron and steel slag) may be more reactive but are much less abundant. The LCA examined the fluxes of energy, solids, water, and CO₂ for the processes of extraction (e.g., mineral mining), reactant transportation, preprocessing (e.g., grinding), chemical conversion, postprocessing, product transportation, and disposal or reuse. An example of the CO₂ emissions per 1,000 tCO₂ stored for mineral carbonation processes with net CO₂ mitigation potential is shown in Figure 3.2. As an example, cement kiln dust (CKD) may have reasonable mitigation potential, with associated emissions of about 150 tCO₂ for every 1,000 tCO₂ stored. However, considerations of life-cycle CO₂ emissions must be tempered with consideration of availability of reactant. A review of alkaline industrial wastes such as fly ash, CKD, steel slag, and red mud indicated that in the United States fly ash is most abundant (130 million tons/yr), followed by CKD (~18 million tons/yr), steel slag (~8-10 million tons/yr), and red mud (<5 million tons/yr) (Gadikota and Park, 2014).

Kirchofer et al. (2013) also investigated the CO₂ mitigation potential of mineral carbonation with industry-based available alkaline sources in the United States. CO₂

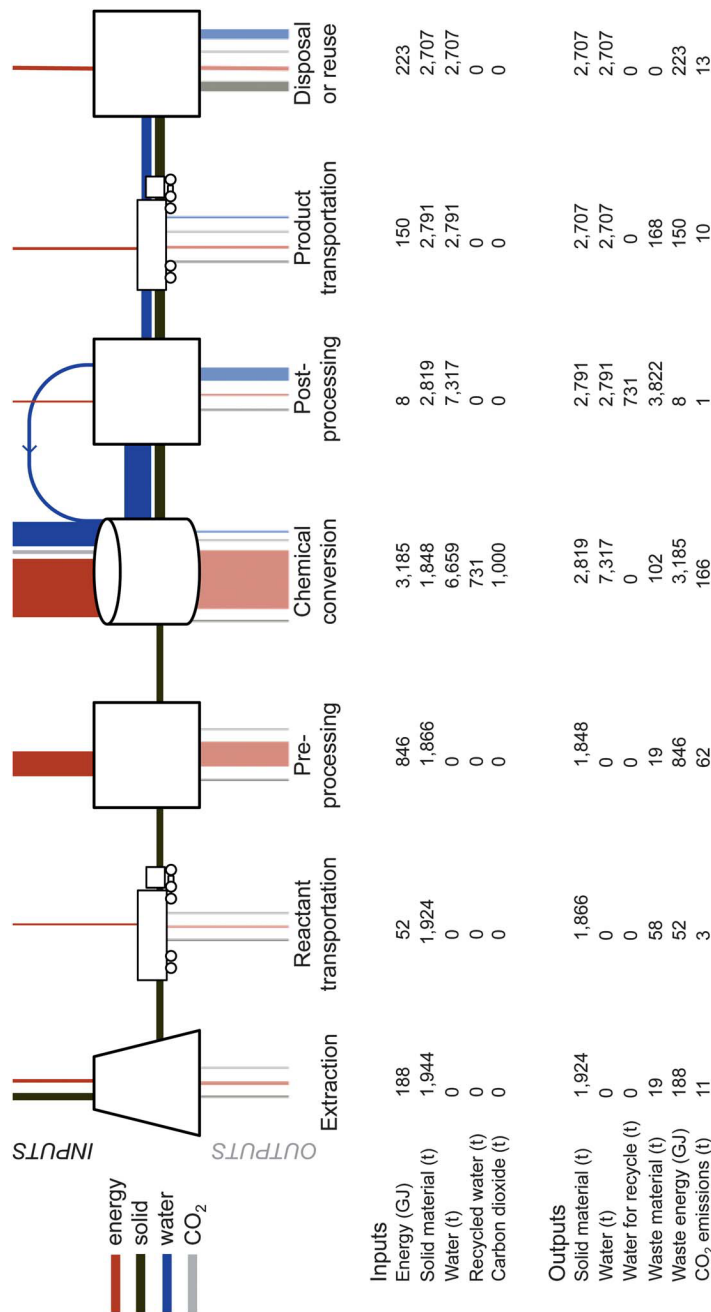


FIGURE 3.1 Life-cycle process model schematic that shows all of the steps associated with mineral carbonation of 1,000 tCO₂ with mined and crushed olivine, which is a silicate mineral rich in Mg²⁺. This schematic shows the number of components required for mineral carbonation, including mineral extraction, transportation, pre-processing (e.g., grinding), chemical conversion, post-processing, product transport, and disposal. The thickness of lines is scaled to the energy and mass fluxes (inputs enter from the top, outputs leave through the bottom). This process does not include the separation of CO₂, and it is questionable whether atmospheric CO₂ is in great enough concentration to achieve adequate conversion. It is likely that the CO₂ would have to be concentrated to some extent to improve mineral carbonation conversion on timescales of interest. Taking into account the total energy (4.65 GJ/tCO₂) as shown for each step results in a cost of ~\$1,000/tCO₂, provided coal is the electric energy source. SOURCE: Kirchofer et al., 2012.

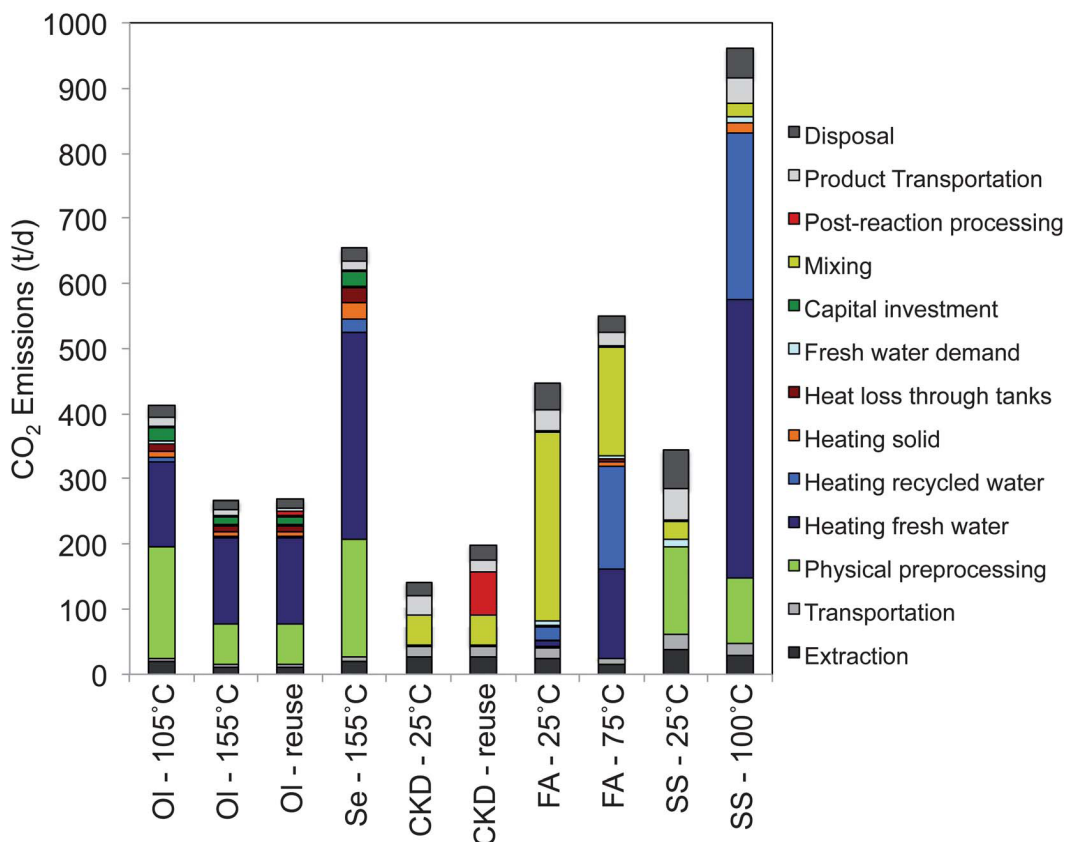


FIGURE 3.2 CO₂ emissions per 1,000 tCO₂/day stored for mineral carbonation processes with net CO₂ mitigation potential (Kirchofer et al., 2012). Ol, olivine; Se, serpentine; CKD, cement kiln dust; FA, fly ash; SS, steel slag. Temperatures refer to reaction temperatures for chemical mixing. Emissions from using cement kiln dust for a mineral carbonation process are estimated to be the lowest, where storing 1,000 tCO₂/day results in 105 tCO₂/day of emissions, or a net mitigation of almost 900 tCO₂/day.

point-source emissions are typically several orders of magnitude greater than the total available industrial byproduct alkalinity in locations across the country. This study found that U.S. industrial alkaline byproducts have the potential to mitigate about 7.5 MtCO₂/yr, of which 7 MtCO₂/yr is captured via mineral carbonation, and about 0.5 MtCO₂/yr is from the avoided emissions associated with the replacement of naturally mined aggregate. Unfortunately, this is only about 0.1 percent of U.S. CO₂ emissions. Including natural and industrial-sourced alkalinity yields a maximum potential of ~1.5 GtCO₂/yr in the United States (Kirchofer et al., 2013); multiplied out over the rest of the century this gives a total potential of ~130 GtCO₂ out to 2100.

In situ accelerated weathering, in which CO_2 reacts with available alkalinity in Earth's surface, may also provide a potentially significant means of sequestering CO_2 . For instance, Kelemen and Matter (2008) estimate that there is an approximate sequestration capacity of 1 trillion tons of CO_2 within 3 km of the surface in the Sultanate of Oman through mineral carbonation of peridotite. Alternatively, mineral carbonation with alkalinity present below the seafloor is interesting to note, although the feasibility of such an approach may be questionable. In particular, Kelemen et al. (2011) report that approximately 1,000 trillion tons of CO_2 may be mineralized in a section 10 km wide by 3 km deep along the world's slow-spreading ridges.

The accelerated weathering concepts explored in this section are the result of theoretical explorations and limited laboratory testing. No demonstration or pilot plants exist to date. Nevertheless, the underlying geochemistry of chemical weathering and the relevant characteristics of global biogeochemical cycles are well established (Berner and Berner, 2012). Most of the engineering is straightforward—mining, crushing, and distributing minerals, or chemical engineering processes that are routinely done at laboratory scale. However, although some scaling estimates have been made (e.g., Harvey, 2008; Ilyina et al., 2013), many issues of scaling have not yet been investigated.

The large mass required if these strategies were to be deployed at a scale commensurate with the climate problem is clearly a major barrier. Proposals that rely on the ocean as a disposal site also face potential ecological and legal challenges. The legal status of such proposals under the London Convention and London Protocol is unclear (see discussion in Chapter 4). Because adding alkalinity to the ocean also helps to counteract ocean acidification, it is thought that direct biological consequences could be positive; however, no field studies have tested this hypothesis.

Because these accelerated chemical weathering approaches are relatively low-tech in their fundamental concept, it should be possible to get improved cost estimates for accelerated chemical weathering facilities and operations. These cost estimates would need to take into account geographically specific conditions; the costs of mined minerals and their transportation are likely to comprise a substantial fraction of overall cost (Figure 3.1) for ocean-based accelerated weathering, whereas land-based accelerated weathering is substantially more expensive to achieve significant impact, as previously discussed.

If such approaches are seriously contemplated, it would be important to first conduct experiments in which marine organisms or ecosystems are exposed to seawater with

the chemistry that would be expected to result from such operations.⁷ For proposals that involve spreading minerals on land, it would be useful to have experiments and analyses aimed at understanding what long-term application would do to these soils and the ecosystems living thereon; also, downstream impacts on streams and rivers would need to be considered.

The committee highlights several important future research directions:

- Investigations into cost-effective methods of enhancing the kinetics of carbonate and silicate mineral dissolution (or other chemical transformations) for CO₂ conversion to bicarbonate or carbonate; potential approaches include mineral pretreatment, enhancement of acid-base reactivity, synergies with biotic activity, enzymes, and electrochemistry;
- Experiments and modeling to determine the environmental benefits, impacts, and fate of (bi)carbonate addition to soils, watersheds, and the ocean;
- Better determining the environmental impacts of mineral extraction and seawater pumping (where needed), especially relative to downstream environmental benefits and relative to the impacts of other CDR methods;
- Testing and modeling various approaches at meaningful scales to better determine the life-cycle economics, net cost/benefit, optimum siting, and global capacities and markets of accelerated mineral weathering in the context of CDR.

In summary, only laboratory-scale experiments of ocean-based accelerated weathering have been carried out thus far. Further research at meaningful scales could help assess concerns related to economics, global capacity, and associated environmental and sociopolitical risks. However, this technology is currently only at an intermediate level, and this approach may have significant environmental and sociopolitical risks since it concerns the ocean. This approach has the potential of cumulative CDR of ~100 GtCO₂ out to the year 2100 at a rate of ~1 GtCO₂/yr with estimated costs in the range of \$50/tCO₂ to \$100/tCO₂ (McLaren, 2012; Rau et al., 2013).⁸ Land-based mineral carbonation approaches have been investigated at limited scale as well and are likely also at an intermediate technology level, but they have minimal sociopolitical risks, except for risks associated with the mining and disposal of large masses of material. Intermediate environmental risks may exist due to the uncertainty of the effects of

⁷ The results of such experiments could be compared to expected effects on organisms and ecosystems from increasing pH due to ocean acidification.

⁸ Rau et al.'s estimate includes an ocean-land requirement of $<7 \times 10^5$ km²/GtCO₂ captured per year and assumes wind as an energy resource; the total of 85 GtCO₂ assumes approximately 1 GtCO₂/yr for 85 years until 2100.

mining large masses of minerals, in the case of ex situ mineralization, and injection of large amounts of alkalinity and CO_2 , in the case of in situ mineral carbonation. Land-based approaches using silicate minerals have been estimated to have a potential capacity of roughly 4 Gt CO_2 /yr with an estimated cost of \$23/t CO_2 to \$66/t CO_2 (IPCC, 2014b; Rau and Caldeira, 1999; Rau et al., 2007). In considering ex situ mineral carbonation, these low cost estimates do not consider all steps of preparation and utilization of CO_2 and the minerals as outlined in Figure 3.1. Taking into account the total energy (4.65 GJ/t CO_2) as shown for each step results in a cost of ~\$1,000/t CO_2 provided coal is the electric energy source (Kirchofer et al., 2012).

OCEAN FERTILIZATION

A natural biological pump exists in the sea: planktonic algae and other microscopic plants take up CO_2 at the ocean surface and convert it to particulate organic matter. Some of this organic matter settles into the deep ocean and serves as food for animals, bacteria, and other microorganisms that respire and reverse the reaction, converting organic carbon back to CO_2 , which is re-released at depth. The net result of the biological pump is to sequester inorganic carbon in the deep ocean and thus maintain a lower preindustrial atmospheric CO_2 . Numerical modeling studies suggest that variations in the magnitude and geographic patterns of the biological pump could drive changes in atmospheric CO_2 of a few tens to perhaps more than 100 ppm over timescales of several decades to centuries (Marinov et al., 2008; Sarmiento and Gruber, 2006). To a first-order approximation, the present-day biological pump is thought to be in steady state and does not materially influence the concentration of anthropogenic CO_2 in the atmosphere, and the current rate of ocean uptake of anthropogenic CO_2 is governed by physical-chemical processes and ocean circulation (Sabine and Tanhua, 2010).

The strength of the marine biological pump and resulting ocean carbon sequestration depends, among other factors, on the quantity of the phytoplanktonic nutrients nitrogen and phosphorus in the global ocean and the completeness with which the supply of these nutrients to the surface ocean are utilized by phytoplankton. There are several mechanisms by which a natural or deliberate human perturbation of the biological pump could potentially enhance the net uptake and ocean sequestration of CO_2 from the atmosphere. First, if a limiting nutrient like nitrate or phosphate is added to the ocean from an external source, the utilization of that nutrient by primary producers would increase the net formation of organic matter. That additional organic material would ultimately be exported to the ocean interior and respired as CO_2 , thus increasing deep-ocean CO_2 sequestration. Second, there are regions in the ocean where some

of the nutrients brought from depth to the surface are not consumed before they are returned to depth by ocean circulation. If the efficiency of nutrient utilization in those regions, primarily in the Southern Ocean, were to be somehow enhanced, more carbon would be stored in the intermediate and deep ocean. Third, if the elemental ratio of carbon to nutrients in organic matter were to increase from the average value at present, then the net new flux of carbon to depth would also increase. Fourth, a reduction in the biological formation of particulate inorganic carbon in the surface ocean would increase surface alkalinity and enhance ocean carbon sequestration. Finally, most of the organic matter produced by plankton is respired in the upper few hundred meters of the water column, with only a small fraction reaching the mid-depth to deep ocean where the respired CO_2 is isolated from the atmosphere for many decades to centuries because of the relatively slow overturning circulation of the ocean. In model simulations, increasing the depth where sinking particles are respired back to CO_2 results in increased ocean carbon sequestration (Kwon et al., 2009). These scenarios are not mutually exclusive and could arise because of changes in ocean circulation, external nutrient and trace-metal inputs, and plankton food-web dynamics. One perturbation will be climate change forced by the combustion of fossil fuels.

In a future warmer world, climate change will almost certainly alter ocean circulation and stratification, which in turn may also affect the aforementioned biological processes that are critical to the biological pump (Sarmiento et al., 1998). Model simulations suggest that the changes in ocean physics and biology may be sufficient to reduce by a small degree the ocean's ability to remove anthropogenic CO_2 and store inorganic carbon (Arora et al., 2013). Some studies have suggested that climate change is already reducing ocean carbon uptake at least regionally (e.g., Le Quéré et al., 2009), but this relatively small long-term climate effect is difficult to discern robustly from the limited available historical and present-day observations (McKinley et al., 2011).

Approaches have been proposed to increase the strength of the biological pump (through increasing either the size of nutrient reservoirs or the degree to which they are used) by deliberately adding nutrients to fertilize ocean plankton. The large quantities of nitrogen and phosphorus that must be added to the ocean to significantly affect atmospheric CO_2 render this approach far less practical than iron fertilization, reflecting the fact that the organic matter formed by plankton has a relatively low ratio of carbon to either nitrogen or phosphorus (for example, the carbon-to-nitrogen ratio is only about a factor of 5 to 8). Instead, the focus has been on more modest additions of the essential micronutrient iron because of the large ratios of carbon to iron in planktonic organic matter (1,000 to more than 100,000 on a mole/mole basis; Boyd et al., 2007).

The basic principle behind ocean iron fertilization (OIF) is that by adding iron to surface waters in some specific regions of the ocean, one could stimulate increased growth by phytoplankton, which would increase the completeness with which the natural supplies of nitrogen and phosphorus are used in those waters, increasing the flux of organic carbon into the deep ocean. Under an appropriate set of conditions, the enhancement of the biological pump would result in CDR from the upper ocean and atmosphere and sequestration in the subsurface ocean (Martin, 1990). A primary focus is on the high-latitude surface waters of the Southern Hemisphere that typically have abundant macronutrients (e.g., nitrogen and phosphorus) but low chlorophyll and phytoplankton growth—particularly of large cells that lead to carbon export—relative to other nutrient-abundant regions, because of limitation by low surface iron levels (Martin and Fitzwater, 1988). This discovery resulted in proposals to influence the biological pump's effect on ocean anthropogenic CO₂ uptake through the deliberate addition of iron to the ocean surface (Box 3.2). The Southern Ocean contains the largest area of iron-limited conditions and is the focus of many discussions on ocean iron fertilization approaches; other iron-limited regions, including the subpolar North Pacific and eastern Equatorial Pacific, have been the sites of scientific field experiments on iron addition and are often included in numerical simulations of ocean iron fertilization methods.

Other related ocean biological CDR approaches have been proposed but have been studied in less detail than ocean iron fertilization (Williamson et al., 2012). Fertilization with surface addition of macronutrients, such as bioavailable nitrogen in the form of urea as well as phosphate (Lampitt et al., 2008), has the advantage that it can be applied in low-latitude, nutrient-poor surface waters and has possible co-benefits because of enhanced biological productivity. However, as already noted, there are drawbacks relative to micronutrient fertilization because of the much larger mass requirements associated with the plankton biological needs of nitrogen and phosphorus relative to carbon. Another proposed alternative would be to artificially enhance ocean upwelling of subsurface nutrients with some form of active pumping method using, for example, wave-driven pipes (e.g., Lovelock and Rapley, 2007). Artificial upwelling has also been suggested as a carbon sequestration method for some specific ocean regions where the supply of excess phosphorus could stimulate nitrogen fixation (Karl and Letelier, 2008). Beyond issues of the technical feasibility of ocean pipes and the resulting cooling of the ocean surface, the major drawback from a CDR perspective is that any upwelled subsurface water with enriched nutrients would also have elevated CO₂ levels that would effectively cancel most, if not all, of the benefit of biological carbon drawdown (Oschlies et al., 2010; Yool et al., 2009).

BOX 3.2 HISTORICAL CONTEXT OF OCEAN IRON FERTILIZATION

“Give me half a tanker of iron, and I’ll give you an ice age,” biogeochemist John Martin reportedly quipped in a Dr. Strangelove accent at a conference at Woods Hole in 1988 (Fleming, 2010). Martin and his colleagues at Moss Landing Marine Laboratories proposed that iron was a limiting nutrient in certain ocean waters and that adding it stimulated explosive and widespread phytoplankton growth. They tested their iron deficiency, or “Geritol,” hypothesis in bottles of ocean water, and subsequently experimenters added iron to the ocean in a dozen or so ship-borne “patch” experiments extending over hundreds of square miles (see text for discussion). OIF was shown to be effective at inducing phytoplankton growth, and the question became this: Was it possible that the blooming and die-off of phytoplankton, fertilized by the iron in natural dust, was the key factor in regulating atmospheric carbon dioxide concentrations during glacial-interglacial cycles? Dust bands in ancient ice cores encouraged this idea, as did the detection of natural plankton blooms by satellites.

This realization led to further questions. Could OIF speed up the biological carbon pump to sequester carbon dioxide? And could it be a solution to climate change? Because of this possibility, Martin’s hypothesis received widespread public attention. What if entrepreneurs or governments could turn patches of ocean green and claim that the carbonaceous carcasses of the dead plankton sinking below the waves constituted biological “sequestration” of undesired atmospheric carbon? Several companies—Climos,¹ Planktos (now out of the business), GreenSea Ventures, and the Ocean Nourishment Corporation²—have proposed entering the carbon-trading market by dumping either iron or urea into the ocean to stimulate both plankton blooms and ocean fishing (Climos, 2007; Freestone and Rayfuse, 2008; Powell, 2008; Rickels et al., 2012; Schiermeier, 2003).

OIF projects could be undertaken unilaterally and without coordination by an actor out to make a point; in fact, one such incident took place off the coast of Canada in 2012 (Tollefson, 2012). However, as this section describes, there are still unresolved questions with respect to the effectiveness and potential unintended consequences of large-scale ocean iron fertilization.

¹ <http://www.climos.com/index.php>.

² <http://www.oceannourishment.com/>.

An extensive series of small-scale iron release experiments have shown that artificially adding iron to high-nitrate, low-chlorophyll regions in the Equatorial Pacific and Southern Ocean does cause increased phytoplankton growth rates and the development of phytoplankton blooms (Boyd et al., 2007; de Baar et al., 2005). Mesoscale iron fertilization experiments also have demonstrated that a shift toward larger phytoplankton species, in particular diatoms, occurs and that the short-term ocean draw-down of atmospheric carbon dioxide increases to varying degree (Coale et al., 1996; Pollard et al., 2009). Collecting evidence of increased sinking of particulate carbon has proved more elusive, in part because of limitations on the duration and scope of field

experiments to date (Buesseler and Boyd, 2003). Few studies have measured well the changes in particle fluxes and respiration rates in the subsurface ocean below a bloom because experiments ended before the bloom terminated or because the patch of fertilized water had expanded to cover a much broader area, making it more difficult to observe changes using sediment traps. Thus, the effect on long-term CO₂ drawdown and increase in ocean carbon sequestration in the interior of the ocean is not well documented and appears to vary substantially across experiments and ocean regions, with examples of both minimal and large sinking particle flux events associated with specific experiments (Martin et al., 2013; Smetacek et al., 2012).

An iron-fertilized increase in sinking organic matter will not necessarily translate directly into a comparable increase in the rate of long-term ocean inorganic carbon sequestration. Much of the sinking organic matter flux due to an iron fertilization-induced bloom will be respired back to CO₂, nutrients, and dissolved iron by bacteria and zooplankton in the upper few hundred meters of the water column, and ocean circulation will carry the resulting excess CO₂ back to the ocean surface, where it can be released back to the atmosphere on relatively short timescales of a few years to decades, unless there is sufficient iron available to support biological transformation of the excess CO₂ back into organic matter (Robinson et al., 2014). Therefore, an important factor is the degree to which the iron released at depth during organic matter respiration remains in the water column or is removed to the sediments through scavenging and particle export. Rapid iron scavenging would imply that ocean fertilization would need to be continued essentially indefinitely to result in permanent carbon disposal from the atmosphere. Alternatively, if a substantial amount of the added iron that sinks with and is released from respired organic particles is not scavenged from subsurface waters, it could limit the escape of the excess CO₂ to the atmosphere when the subsurface water returns to the ocean surface and could extend the duration of enhanced ocean carbon sequestration due to iron fertilization. Enhanced long-term carbon sequestration, typically defined as a duration of more than 100 years, would also occur from the small fraction of sinking particles that reach intermediate or deep waters (greater than 1,000 m).

Because of the large natural background levels and variability of subsurface dissolved inorganic carbon, the direct measurement of small changes in ocean carbon sequestration at depth from ocean iron fertilization experiments is challenging. Furthermore, it is not possible in the field to track the subsequent fate of water parcels for sufficiently long time to quantify the rate of return to the surface ocean. Therefore, estimates of the efficiency of iron fertilization on ocean carbon sequestration are restricted so far to numerical model studies that require a number of assumptions about biological dynamics and iron biogeochemistry. With these caveats in mind, modeling

studies indicate that the potential upper limit for a sustained ocean iron fertilization CO₂ sink is relatively modest at 1.0 to 3.7 GtCO₂/yr⁹ and that the total ocean sequestration capacity until the end of the century is 85 to 315 GtCO₂, assuming continuous iron fertilization of the entire iron-limited Southern Ocean, Equatorial Pacific, and subpolar North Pacific (Aumont and Bopp, 2006; Zahariev et al., 2008).

Early cost estimates for ocean iron fertilization were quite low (<\$10/tCO₂), reflecting the large leverage of the amount of iron added per organic carbon fixed via photosynthesis (e.g., Ritschard, 1992). However, more recent studies factor in new information, suggesting lower biological efficiency leading to carbon export and sequestration and leakage of CO₂ back to the atmosphere (Markels et al., 2011). For example, one estimate of the cost of ocean iron fertilization is approximately \$450/tCO₂ (Harrison, 2013). Improved cost estimates would also require information on technological issues (e.g., iron spreading and approaches to limit scavenging), the efficiency of atmospheric CO₂ uptake, and verification and monitoring requirements.

Studies have identified a number of possible drawbacks to iron fertilization as a CDR method (Buesseler et al., 2008; Strong et al., 2009; Williamson et al., 2012). In particular, the ecological impacts on the marine food web and fisheries due to continuous, extensive iron fertilization may be substantial but are poorly characterized. It is also likely that iron fertilization will have downstream effects on nutrient supply, and thus productivity and food web dynamics, in other ocean regions. An intended consequence of ocean iron fertilization involves shifting plankton community composition toward larger cells that will lead to enhanced downward-sinking flux; the long-term impact of this shift on higher trophic levels, including fish, seabirds, and marine mammals, is not well known but may be addressable in part by studying analogous regions with substantial natural iron fertilization. Iron addition often stimulates the growth of *Pseudonitzschia* diatom species, some of which are associated with toxin-producing harmful algal blooms (Moore et al., 2008). In the case of a specific iron addition experiment in the subpolar North Pacific Ocean, the iron-stimulated *Pseudonitzschia* diatoms were shown to produce domoic acid, a neurotoxin that has the potential to harm fish, marine mammals, and humans (Trick et al., 2010).

A number of scientific studies have raised concerns about how ocean iron fertilization may potentially also alter ocean biogeochemistry. Changes in the air-sea fluxes of climate-active trace gases such as dimethylsulfide, methane, and nitrous oxide (N₂O) could in principle either partially cancel out or amplify the benefits from enhanced ocean CO₂ uptake (Diaz and Rosenberg, 2008). A substantial component of ocean N₂O

⁹ Only two significant figures reported here.

production is thought to arise from microbially driven nitrification of ammonia and organic nitrogen released from sinking particles in the upper ocean. Nitrification is expected to increase due to iron fertilization, and because N_2O is a much more powerful greenhouse gas than CO_2 , the effect could be to greatly diminish the climate impact of iron fertilization (Barker et al., 2007; Jin and Gruber, 2003). There is also the potential for the release of methyl halides to the atmosphere that might lead to possible depletion of stratospheric ozone (Wright, 2003). Increased export of organic carbon to the subsurface ocean would also likely reduce local subsurface dissolved oxygen levels, exacerbating the declines in subsurface oxygen already expected under a warmer climate. A resulting expansion of low-oxygen, hypoxic regions of the coastal or open ocean would potentially have significant biological ramifications (Keeling et al., 2010). Iron fertilization on a large scale could potentially also have downstream effects by reducing the nutrient supply to low-latitude ecosystems. Although ocean iron fertilization would act to remove CO_2 from the surface ocean and transport it to depth, the effects on partially mitigating ocean acidification in surface waters due to rising atmospheric CO_2 levels would be minimal at best and would somewhat increase the rate of acidification of subsurface waters (Cao and Caldeira, 2010). In addition to these concerns over the effectiveness and environmental impacts of OIF projects, there are significant ethical and legal concerns as well. These are discussed further in Chapter 4.

Looking forward, the committee highlights several important future research directions:

- Understanding the effectiveness of iron inputs on stimulating biological organic carbon production and increasing carbon export;
- Determining the fate of the sinking organic carbon and iron in the subsurface ocean as a result of deliberate ocean iron fertilization;
- Assessing potential downstream effects that may limit biological productivity or change other aspects of biogeochemistry in other regions;
- Detection and accounting of net changes in subsurface ocean carbon sequestration and the effective lifetime of the carbon sequestration; and
- Understanding the ecological and biogeochemical consequences of extended and large-scale iron fertilization.

In summary, current limitations of ocean iron fertilization as a viable CDR method include the limited knowledge regarding the method's effectiveness in regard to carbon capture, concerns regarding the environmental impacts and cost of large-scale and sustained OIF, and the associated ethical and legal issues. Although about a dozen ocean iron fertilization field experiments have been conducted, their purpose was fundamental scientific research primarily related to the basic controls on ocean biology and biogeochemistry. Many unresolved issues remain regarding scalability, ef-

ficacy, verification, and environmental impacts. Given these limitations and unknowns, the committee concludes that the risks and costs currently outweigh the benefits. The committee considers this an immature CDR technology with high technical and environmental risk.

BIOENERGY WITH CARBON CAPTURE AND SEQUESTRATION AND DIRECT AIR CAPTURE AND SEQUESTRATION

Bioenergy with Carbon Capture and Sequestration

BECCS is a process in which biomass is converted to heat, electricity, or liquid or gas fuels, followed by CO₂ capture and sequestration. The BECCS cycle (Figure 2.1) begins with plants assimilating CO₂ from the atmosphere via photosynthesis with sufficient sunlight, water, and nutrients (e.g., bioavailable nitrogen and phosphorus or fertilizers) as additional inputs. The biomass is then used in either an energy generation (electricity or process heat) or chemical process plant, thereby creating CO₂ and water vapor. Biomass also can be used to produce liquid fuels such as ethanol or methanol, gas fuels such as hydrogen, or engineered algal systems designed to directly produce hydrocarbons. The CO₂ is captured in a similar manner to how it would be captured from point-source emitters firing coal or natural gas.¹⁰ To form liquid fuels, the synthesis gas would be catalytically reacted through a Fischer-Tropsch process.¹¹ The formation of alcohols, polymers, and various carbon-based chemicals is also possible through this catalytic process. Formation of liquid fuels does not cause a net sequestration of carbon; it involves chemical conversion for use as an energy source and emission to the atmosphere.

Current estimates show that if BECCS were deployed to its theoretical maximum feasible amount, it could account for a significant portion of the world's energy supply. Literature estimates for bioenergy potential range from 50 to 675 EJ/yr (Berndes et al., 2003). Many integrated assessment models (Azar et al., 2010; Rao et al., 2008; Riahi et al., 2011; Thomson et al., 2011) assume large-scale bioenergy usage by the end of the century, in the range of 150 to 400 EJ/yr.

Both the availability of land for biomass cultivation and the need to transport bulky biomass to processing facilities severely limit the feasible use of bioenergy. The higher

¹⁰ Capture technologies from point-source emitters (e.g., coal- and natural gas-fired power plants) include absorption via amine scrubbing (or other chemical solvent), adsorption, and membrane technologies for pre- and postcombustion applications (Wilcox, 2012).

¹¹ A Fischer-Tropsch process is a series of chemical reactions that converts gas-phase carbon monoxide and hydrogen into liquid hydrocarbons.

reported estimates of energy from bioenergy, 200 to 400 EJ/yr (Azar et al., 2010),¹² assume that diets change dramatically in response to increasing carbon prices, because these costs become embedded into land rents and food prices, leading to a shift from products with high land requirements, such as beef, to products with lower land requirements, such as grains (Wise et al., 2009). It is assumed that these effects are not undercut by the dramatically increasing growing global population or by increased global affluence. Edmonds et al. (2013) report that reduced herd sizes have the potential to free up 4.5 million km² of pastureland and 1.2 million km² of cropland,¹³ allowing for the expansion of bioenergy production. To put this into perspective, 200 EJ/yr (Azar et al., 2010) is roughly equal to current world oil consumption (190 EJ/yr) and represents ~40 percent of today's global energy production (550 EJ/yr).¹⁴ In these scenarios, about 80 to 100 EJ/yr is derived from byproducts of agriculture and forest industries (Azar et al., 2010), with the remaining 180 to 300 EJ/yr coming from dedicated energy crops that require land, water, and nutrients. Biomass growth at this scale requires extensive land area. More specifically, 100 EJ/yr may require up to 500 million hectares of land, assuming an average biomass yield of 10 tons of dry biomass per hectare annually. For comparison, about 1,600 million hectares are currently planted with agricultural crops, and an additional 3,400 million hectares are used for pasture (FAO, 2010). Global food demands are projected to nearly double over the next 50 years (Tilman et al., 2001), which will, in the absence of dramatic yield increases or diet changes, put energy crops in direct competition with food crops for arable land. There is no empirical evidence that the globe is inclined to move away from animal agriculture; rather, demand for meat is increasing globally (Foley et al., 2011).

Large-scale deployment of BECCS would have risks and complications; it is not materially relevant until such time as fossil fuel use is limited and linking CCS with bioenergy use has a net benefit to the climate. Prior to that point, there is no difference in net carbon emissions to the atmosphere whether the CCS is tied to bioenergy or fossil fuel use. Large-scale expansion of biomass plantations may displace forests that have significant biodiversity that the new growth would lack. Primary forests tend to have greater biodiversity than secondary ones (Barlow et al., 2007; Lindenmayer and Hobbs, 2004; Zurita et al., 2006), and restored grasslands and forests are known to have reduced biodiversity compared to neighboring native ecosystems (Camill et al., 2004). In addition, large old-growth forests and undisturbed grasslands have significant

¹² For reference, Azar et al., (2010) report that 100 EJ/yr from bioenergy, if used in conjunction with carbon capture and sequestration (CCS), would remove 2.5 GtC (9.2 GtCO₂).

¹³ For reference, the state of Alaska has a total area of 1.7 million km².

¹⁴ <http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=44&pid=44&aid=2>; <http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=5&aid=2&cid=regions&syid=2008&eyid=2012&unit=QBTU>.

amounts of carbon sequestered, and conversion to other land uses usually leads to large greenhouse gas emissions such that it would take decades or more to provide a net reduction in the atmospheric carbon dioxide stock as a result of bioenergy on these lands (Creutzig et al., 2012; IPCC, 2011c; Mitchell et al., 2012; Tilman et al., 2009).

Smith and Torn (2013) focused on using switchgrass specifically as the biomass feedstock for BECCS and report 200 million hectares of land (20 times the area currently used for U.S. bioethanol production), 20 Tg/yr of nitrogen (20 percent of global fertilizer production), and 4,000 km³/yr of water (equal to current global water withdrawals for irrigation and 4 percent of total renewable water resources) would be required to remove 1 PgC/yr (3.7 GtCO₂/yr). Hence, adoption of bioenergy reliance at this scale will be constrained by available land and resources and the secondary impacts on greenhouse gas emissions (e.g., N₂O). One area of research is to identify energy crops with lower water, nutrient, and energy requirements and the capacity to grow on marginal agricultural lands (Heaton et al., 2008; McLaughlin and Walsh, 1998; Msangi et al., 2007).

According to Kriegler et al. (2013), the costs associated with BECCS are lower than the most optimistic DACS¹⁵ case (Lackner, 2010) up to a removal of 12 GtCO₂/yr, and then the costs increase abruptly due to biomass supply limitations. To put this number into context, CO₂ emissions from fossil fuel combustion were 31.6 Gt in 2011 (IEA, 2011). They argue that when BECCS approaches levels of between 13 and 14 GtCO₂/yr, it will be outcompeted by DACS in terms of cost. Their model (ReMIND) also assumes a sequestration potential of 3,670 GtCO₂ with an injection rate of 0.5 percent per year, which results in an upper bound of 18 GtCO₂/yr. Although this capacity of CO₂ sequestration is consistent with Dooley's (2013) "practical" capacity estimates (3,900 GtCO₂), it is important to keep in mind that today with the existing five CCS projects in place (see below section, Geological Sequestration of Carbon Dioxide), sequestration is only taking place on the order of MtCO₂/yr. In addition, the IEA 2013 CCS Roadmap (IEA, 2013b) estimates that an increase to ~7 GtCO₂/yr through 2050 is required in order to prevent a 2°C increase in warming, among other strategies including nuclear power, efficiency and fuel switching, and renewables. Hence, it is uncertain whether the injection and sequestration of 18 GtCO₂/yr is a reasonable estimate. Furthermore, these studies are misleading since none of the cost estimates include compression or sequestration, but only capture. In addition, it is important to keep in mind that there are many challenges associated with accurately determining sequestration potential and that geological sequestration technologies are still in their infancy (see Benson et al. [2012] and section Geological Sequestration of Carbon Dioxide, below). The seques-

¹⁵ See next section, Direct Air Capture and Storage.

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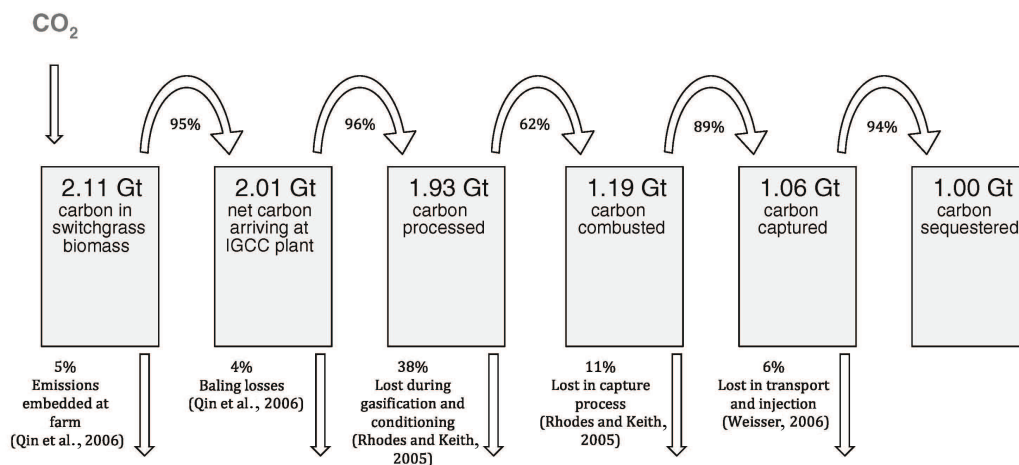


FIGURE 3.3 BECCS carbon flow. Carbon losses upon processing switchgrass to a useful fuel. SOURCE: Smith and Torn, 2013.

tration potential of CO_2 may ultimately dictate the viability and impact of BECCS and DACS as CDR approaches.

Additionally, an important aspect of BECCS to consider is the CO_2 emissions associated with the energy required to process the biomass for gasification or combustion. In the absence of CO_2 sequestration, bioenergy from biomass is not inherently a carbon-neutral process. Figure 3.3 shows an example of the process of gasifying switchgrass. Initially the switchgrass has 2.1 GtC (7.7 GtCO_2), but after drying, processing, and gasifying, there is a resulting 1.06 GtC (3.9 GtCO_2) separated from the synthesis gas and finally 1.00 GtC (3.67 GtCO_2) that will ultimately become stored. Hence, storing 1 GtC (3.67 GtCO_2) requires fixing 2.1 GtC (7.7 GtCO_2) considering the carbon losses along the life cycle of the process. The high carbon-to-energy ratio of bioenergy feedstocks (roughly equal to that of coal and half that of natural gas for dry biomass) and the decrease in net energy resulting from the combustion of bioenergy feedstocks with a high moisture content mean that, in the most common situation, there is lower net reduction in GHG emissions relative to using the same CCS capacity with fossil fuel-generated energy, particularly natural gas-generated energy. If the amount of fossil fuel and bioenergy burned is held constant there is no net reduction in atmospheric CO_2 stocks if CCS is deployed to sequester bioenergy (BECCS) versus fossil fuel-generated carbon dioxide. BECCS is important as a CDR approach once fossil use is limited, and CCS capacity can be used effectively to drive energy emissions net negative.

Looking forward, the committee highlights several important future research directions:

- Small-scale boiler redesign for co-firing natural gas with biomass and
- Advanced technologies for drying biomass at the recovery site to minimize water transport costs and heating inefficiencies.

In summary, the technological readiness of BECCS is similar to that of CCS. The use of biomass as an energy feedstock as practiced in the United States is currently dominated by its use for process heat (EIA, 2013a). Further advances in boiler and gasification technologies will assist in the potential for increased bioenergy use. Similarly, the costs are on the order of conventional CCS at ~\$60/tCO₂ to \$250/tCO₂ unless less expensive alternative CO₂ capture and sequestration methods can be used. The cumulative CDR theoretical potential of BECCS is large at >1,000 GtCO₂ removed and stored by 2100 (Kriegler et al., 2013; Lenton and Vaughan, 2009) at a rate of 15 to 18 GtCO₂/yr (Azar et al., 2010; Kriegler et al., 2013). (Note that the rate in the near term, i.e., out to 2050, may only be up to 3 to 10 GtCO₂/yr [IPCC, 2014b].) However, that potential is likely to be significantly constrained for some time, if not indefinitely, by the need for most arable land to be used to meet global food demand and the competing demand to use global CCS capacity to sequester fossil fuel emissions.

Direct Air Capture and Sequestration

Direct air capture (DAC) refers to chemical scrubbing processes for capturing CO₂ directly from the atmosphere via absorption or adsorption separation processes. Although other abiotic (and biotic) processes can also directly remove CO₂ from air, DAC is distinguished by producing concentrated CO₂ as its end product. Following CO₂ capture, the material used to carry out the separation (e.g., amine- or hydroxide-based sorbents) must then be regenerated; this leads to the production of a near-pure stream of CO₂, which can be used (e.g., enhanced oil recovery, chemical production, or other uses) or sequestered.¹⁶ The separation technologies for DAC are similar, but not necessarily identical, to those used in conventional CCS, in which CO₂ is captured from point sources where CO₂ concentrations are much higher, such as coal-fired power plants or chemical plants producing ammonia or ethylene oxide. Although chemical absorption-based separation employing amines for point-source capture of CO₂ is well established (the first patent was filed in 1930¹⁷), it is not clear that this technol-

¹⁶ The process of DAC with sequestration is referred to as DACS.

¹⁷ Chemical scrubbing using amine-based absorption is often referred to as the current state-of-the-art technology for point-source capture of CO₂ and is a technology that has been ongoing since the first patent filed by Bottoms in 1930.

ogy will be the primary solution for the required scale of significant CO₂ reductions due to its negative environmental impacts, water requirements, and moderately high cost. Solvent-based approaches to chemically scrubbing CO₂ out of the atmosphere are considered here without focus on solid sorbents due to the infancy in adsorption-based processes compared to solvent-based processes for CO₂ separation. There has yet to be a study carried out that involves a detailed cost analysis of an adsorption process from capture to regeneration of CO₂ from the atmosphere.

More specifically, the primary difference between DACS and CCS is that the CO₂ concentration in air is 100 to 300 times lower than in the flue gas of a gas- or coal-fired power plant, respectively. The more dilute a system is, the more energy intensive the capture or separation process is. As shown in Figure 3.4, the minimum amount of energy required to capture CO₂ from air is 2 to 10 times the amount required to capture CO₂ from point sources. For this and related reasons, the cost of capturing CO₂ from air will be higher than from point sources, and DACS is likely to become attractive only after CCS has been widely implemented.

There are other important differences between DAC and point-source capture. The design of an absorbing unit for DAC is likely to be large in terms of its cross-sectional area, but very shallow due to pressure-drop limitation requirements (Figure 3.5), whereas a similar unit for point-source capture is likely to be tall and potentially thin by comparison (Figure 3.6). For example, a 500-MW coal-fired power plant with a plant size of about 15 ha¹⁸ emits on average 11,000 tons of CO₂ per day. Using current state-of-the-art technology based on amine scrubbing, capturing 90 percent of the CO₂ (i.e., 10,000 tons) requires 2 ha, or 13 percent of the footprint of the power plant. Alternatively, capturing 10,000 tons of CO₂ per day directly from the air, assuming an air flow rate of 2 m/s, requires about 15 ha, equal to the land area of a 500-MW power plant (EPRI, 2010). Capital costs generally scale with land area; that is, more units will be required to capture the same amount of CO₂ and will generally require more land area. The energy required (shown in Figure 3.4) generally relates to operating and maintenance costs, where overall costs are the sum of capital costs plus operating and maintenance costs.

Costs of DAC vary in the literature significantly due to the different underlying assumptions factored into the costs (APS, 2011; Holmes and Keith, 2012; House et al., 2011; Mazzotti et al., 2013). In particular, the studies of the American Physical Society (APS), Holmes and Keith, House et al., and Mazzotti et al. are the only ones considered in this cost comparison since they represent the few works that explicitly outline

¹⁸ Roughly the size of 15 football fields.

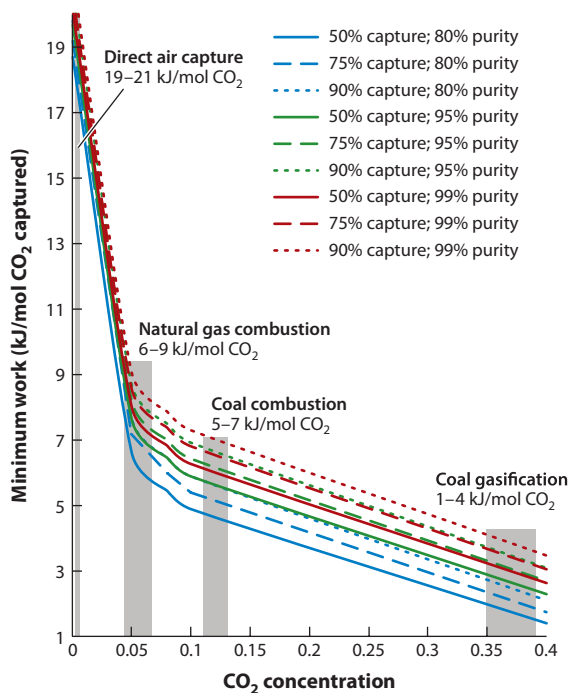


FIGURE 3.4 Comparison of minimum work for CO₂ capture for various capture percentages and purity percentages for applications spanning the extremely dilute atmosphere to the concentrated fuel gas of coal gasification. The more dilute a system is, the greater the energy required for separation. For instance, direct air capture is more energetic than separation from natural gas combustion, which is more energy intensive than separation from coal combustion flue gas (Wilcox et al., 2014).

whether capture and/or regeneration are included in their cost estimates. Although adsorption-based approaches have also been carried out for DAC applications (Choi et al., 2011; Wang et al., 2011), these approaches are not considered explicitly in this report since they have yet to be presented at the demonstration scale in detail in the peer-reviewed literature in a detailed enough fashion. Once CO₂ is captured, the sorbent or solvent used must be regenerated for reuse, producing a near-pure stream of CO₂ for pipeline compression. Table 3.1 highlights several studies from the literature with the underlying assumptions considered in the cost estimates. For instance, House et al.'s \$1,000/ton estimate is based on the first and second laws of thermodynamics, assuming 90 percent capture and 95 percent purity combined with a Sherwood analysis based on the dilution of CO₂ in the atmosphere. In addition, this cost assumes the energy source is CO₂ free since using natural gas or coal would result in greater

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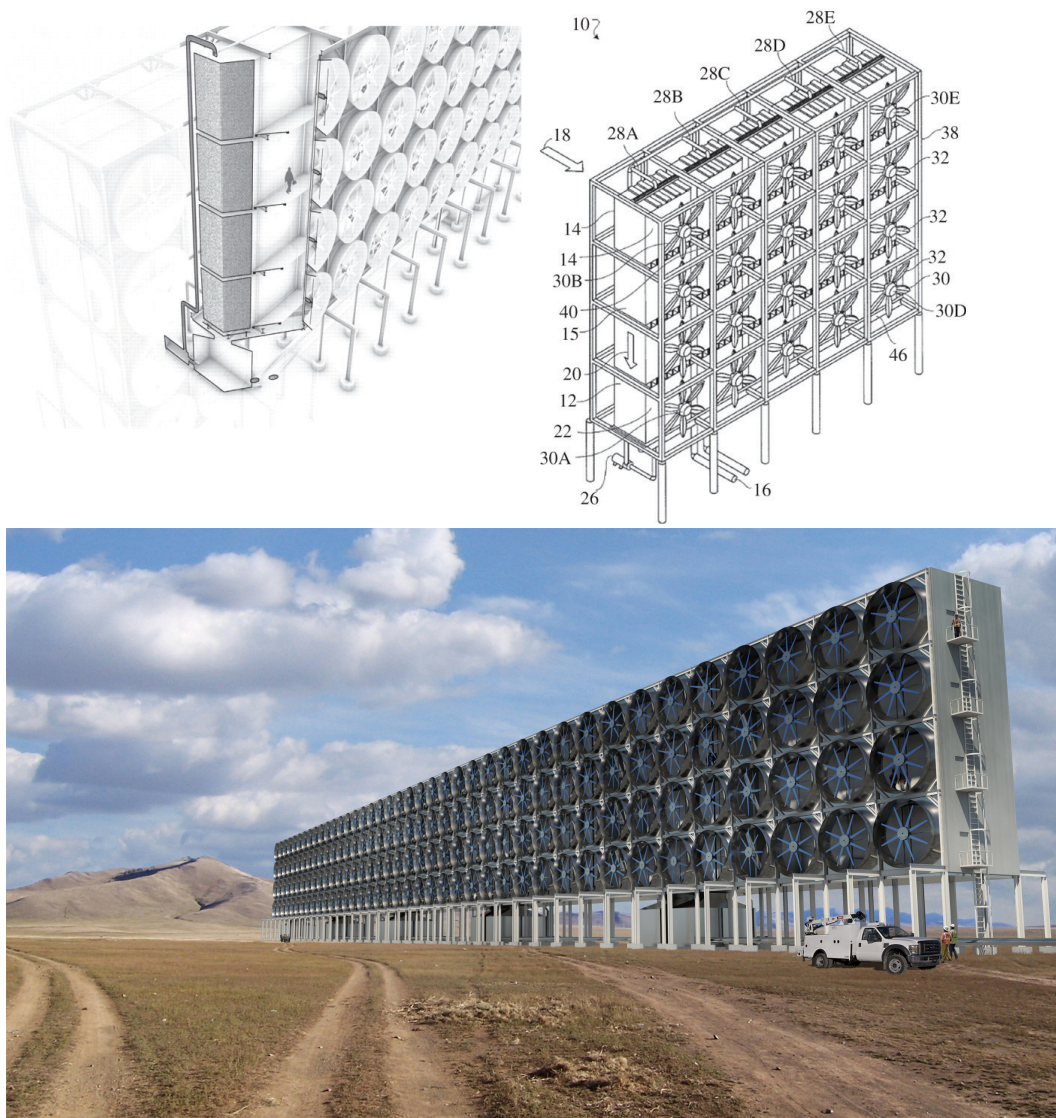


FIGURE 3.5 Carbon Engineering's slab air-contactor design is shown as an example of the design of a DAC plant. The surface area is optimized to achieve maximum air contact for reasonable CO_2 capture, and the width of the column is shallow to minimize pressure drop and subsequent energy requirements. Comparing with Figure 3.6, it is clear that the design and footprint of a separation system is dependent on the starting CO_2 concentration. SOURCE: Holmes and Keith, 2012 (top); Carbon Engineering, Ltd. (bottom).



FIGURE 3.6 Conventional amine solvent plant for CO₂ separation at the National Carbon Capture Center in Wilsonville, Alabama. This is a demonstration plant that bridges technologies from the bench scale to the pilot scale, and the absorber unit that is currently in place captures 3,650 tCO₂/yr. In contrast to the air contactor used for extremely dilute air capture, this flue-gas contactor (absorption column) can be tall for increased CO₂ separation due to the inherent driving force of the flue-gas stream. This image provides an example for dimensional comparison to the DAC plant in Figure 3.5, not a comparison of scale as the annual removal rate by the National Carbon Capture Center is small since it is for demonstration purposes only. SOURCE: Courtesy of Frank Morton, Business Development Manager of the National Carbon Capture Center, Southern Company.

TABLE 3.1 Comparison of Assumptions and Costs of DAC in the Literature

Cost [\$/tCO ₂ captured]				
Capture	Regeneration	Total	Assumptions	Reference
Yes	Yes	1,000	Calculation based on minimum work. Capture and regeneration included.	House et al., 2011
Yes	Yes	376-600	Optimization case study. Counterflow contactor. Considered air velocity, liquid velocity, and recovery as decision variables. Capture and regeneration included.	APS, 2011; Mazzotti et al., 2013
Yes	No	60	Optimization case study. Cross-flow contactor. Air velocity and mass-transfer coefficient as decision variables. Only capture included.	Holmes and Keith, 2012

CO₂ emissions than the CO₂ captured. Because this estimate is based on the minimum work required to separate CO₂ from a gas mixture, capture and regeneration are both inherently included. In the case of the APS report and the more recent work of Mazzotti et al., both capture and regeneration are included in their estimates, which range from \$400/tCO₂ to \$600/tCO₂ captured. The study by Mazzotti et al. was an optimization based on a case study that assumed capture would take place in a conventional absorption process (tall and thin tower as shown in Figure 3.6) with the flue gas and solvent contacting in a counterflow configuration. The decision variables considered in their optimization were air and liquid velocities and percent capture. In the recent work of Holmes and Keith, only the cost of capture was considered (\$60/tCO₂ captured) with a cross-flow air contactor (high cross-sectional area and thin unit as shown in Figure 3.5) and air velocity and the mass-transfer coefficient being the decision variables in their optimization procedure. Again, given these differences in assumptions and the decision to focus on just half of the story in some cases, it is difficult to directly compare these estimates. By comparison, the cost of CO₂ capture from a coal-fired power plant is about \$100/tCO₂ (Al-Juaied and Whitmore, 2009; Deutch and Moniz, 2007; DOE, 2010; IPCC, 2005).

None of the cost estimates above include compression or sequestration, which is required for DAC to be a CDR technology. In addition, since there has not been a DAC plant built to capture CO₂ to date, costing such a design is a difficult task; such a system may look quite different from that used to capture CO₂ from more concentrated sources.

Similar to BECCS, in order for DACS to be a viable component for reducing global warming, the sequestration capabilities have to be well defined. Reservoir quality, proximity to capture plant, and injection rates will all dictate the feasibility, capacity, and rate associated with the CDR from a DACS approach. In addition, safety, public perception, and sequestration reliability will all be primary factors (further discussion of geological sequestration is in the next section). Also, alternative uses of the concentrated CO₂ need to be considered, for example, its conversion via accelerated mineral weathering to solid carbonate or dissolved bicarbonate for stable ocean sequestration (see Accelerated Weathering Methods and Mineral Carbonation). One advantage of DACS over CCS and BECCS is that capture equipment can be sited close to sequestration or utilization¹⁹ sites (if the CO₂ is to be utilized) without regard to considerations that influence power plant siting (e.g., fuel supply and electricity transmission).

Overall, looking forward, the committee highlights several important future research directions in direct air capture:

- System optimization that couples material properties for CO₂ separation to the process properties;
- In terms of technological advancements, determining if overlap in separation technologies exists between dilute versus concentrated CO₂ sources;
- Alternative CO₂ conversion, sequestration, or use options other than underground injection of concentrated CO₂; and
- Systems analysis between DAC plant design coupled to noncarbonized energy resources such as solar and wind.

In addition, a possible alternative to DAC for which further research could provide benefits is the internal consumption of or the extraction of CO₂ from seawater (Box 3.3).

In summary, DAC is an immature technology with only laboratory-scale experiments carried out to date and demonstration-scale projects in progress, with limited public results (see, for example, Choi et al., 2011; Holmes and Keith, 2012; Lackner, 2009; it is too early for peer-reviewed studies to have documented the performance of

¹⁹ Utilization includes enhanced oil recovery (EOR), exhaust gas recirculation, and chemical production.

BOX 3.3 SEAWATER CAPTURE

As shown in Figure 2.1, the ocean contains 50 times more carbon than the atmosphere, and about 28 percent of the CO₂ emitted by humans is dissolved in the ocean (see Table 2.1). The concentration of carbon in seawater is more than 100 times the concentration of carbon in air per unit volume (100 mg/L versus 0.8 mg/L in air), but 6 times less per unit mass (100 mg/kg versus 600 mg/kg). For natural seawater (pH ~ 8), most of the dissolved carbon is in the form of bicarbonate ion (HCO₃⁻). Consuming CO₂ in seawater via in situ biological means (see Ocean Iron Fertilization) or by chemical or geochemical reactions (see Accelerated Mineral Weathering with Land-Ocean Sequestration) causes the partial pressure of CO₂ (pCO₂) in that seawater to decline. As ocean pCO₂ drops below the pCO₂ of air, CO₂ will passively diffuse from air into the ocean and will mostly equilibrate into other forms, principally HCO₃⁻, thus removing and sequestering air CO₂. Alternatively, CO₂ can be extracted from seawater by heating, placing under a vacuum, purging or bubbling with a non-CO₂ gas, or acidification via means other than CO₂ addition. In this vein, Eisaman et al. (2012) demonstrated the extraction of nearly 60 percent of the dissolved carbon in seawater in the form of CO₂ using bipolar membrane electro dialysis. Following removal of CO₂ from seawater, the pCO₂ of the remaining seawater would be reduced and hence would become a sink for atmospheric CO₂. The electrochemical energy consumption for this nonoptimized process was experimentally observed to be about 240 kJ/mol. Additional energy would be required to pump seawater through the plant. Although this is more than 10 times that given in Figure 3.4 for DAC (~20 kJ/mol), this is a measured value rather than a theoretical minimum. Such energy requirements are substantially lower than the 400 to 1,000 kJ/mol estimated for DAC systems (APS, 2011; House et al., 2011; and references therein). Other marine electrochemical approaches have been proposed (House et al., 2007; Rau, 2008; Rau et al., 2013), with estimated energy expenditures at scale of <300 kJ/mol CO₂. In general seawater capture is much less technologically mature than air capture, so research in this area could yield potential benefits.

some other systems). An additional limitation is the energy-intensive nature of this approach, making it cost prohibitive compared to point-source CO₂ capture. Cost estimates including both CO₂ capture and sorbent regeneration range between \$400/tCO₂ and \$1,000/tCO₂ (House et al., 2011; Mazzotti et al., 2013).²⁰ Point-source CO₂ capture costs are currently lower, but costs for reducing emissions from distributed sources (e.g., replacing large numbers of cars with electric vehicles) may be considerably higher. Benefits of DAC are the flexibility associated with plant placement in addition to its minor environmental impacts. As with BECCS and conventional CCS, DAC needs to be coupled with sequestration in order for negative emissions to take place (Figure 2.2). In addition, the energy source for DAC needs to be free of CO₂

²⁰ The wide range of estimates stems from including both capture and sorbent regeneration steps.

emissions for this approach to be optimally CO₂-emissions-negative. The annual and cumulative CDR potential up to 2100 was considered for the United States only. Assuming that solar energy is used to fuel the DAC process and that ~100,000,000 acres of Bureau of Land Management (BLM) land are available in the southwestern United States, this could lead to a removal of ~13 GtCO₂/yr and a cumulative removal of ~1,100 GtCO₂ up to 2100 (see Table 2.2 as well).

Geological Sequestration of Carbon Dioxide

The sequestration of CO₂ is directly connected with BECCS, DACS, and CCS technologies, as previously discussed. Once CO₂ is captured, it must be sequestered to prevent its return to the atmosphere. Depleted hydrocarbon reservoirs and saline aquifers are the primary options for geological sequestration of CO₂. EOR and coal-bed methane recovery are utilization techniques that inadvertently store some CO₂, but for the most part the CO₂ used in these processes is recovered for subsequent reuse (see Utilization of Carbon Dioxide and Available Markets). Research is ongoing as to whether CO₂ might be used as an enhancement fluid for gas recovery from shale (Firouzi et al., 2014; Heller and Zoback, 2014). To give a sense of scale, cumulative emissions are on the order of 2,000 GtCO₂, which corresponds to a volume of approximately 2,300 km³ (equivalent to Lakes Erie and Ontario combined²¹).

Total capacity estimates show that geological sequestration has the potential to sequester large amounts of CO₂. In *Global Energy Assessment: Toward a Sustainable Future*, Benson et al. (2012) estimate that global sequestration capacities for depleted oil and gas reservoirs are ~1,000 GtCO₂ for coal beds up to 200 GtCO₂ and sequestration in saline aquifers is highly variable between 4,000 and 23,000 GtCO₂ (Benson et al., 2012). A recent study by Dooley (2013) provides updated geologic sequestration capacities, with a global “theoretical” capacity of 35,300 GtCO₂, an “effective” capacity of 13,500 GtCO₂, and a “practical” capacity of 3,900 GtCO₂. The IPCC (2005, 2011a) estimates a minimum sequestration capacity in geologic formations of 550 GtC (~2000 GtCO₂), with the potential to be significantly larger (i.e., thousands of gigatonnes of carbon), due to the uncertainty associated with saline aquifers. In 2012, the U.S. Geological Survey (USGS) identified technically accessible sequestration resources totaling 3,000 GtCO₂ in 36 geological formations in the United States (USGS Geologic Carbon Dioxide Storage Resources Assessment Team, 2013). Figure 3.7 shows the estimated CO₂ sequestration potential of saline aquifers, depleted oil and gas, and coal-bed reservoirs

²¹ The volume of 2,000 GtCO₂ is approximately 2,300 km³ assuming a CO₂ condensed-phase density of 0.02 mol/cm³ (Liu and Wilcox, 2012); the volume of the U.S. Great Lakes can be found here: USEPA (2011).

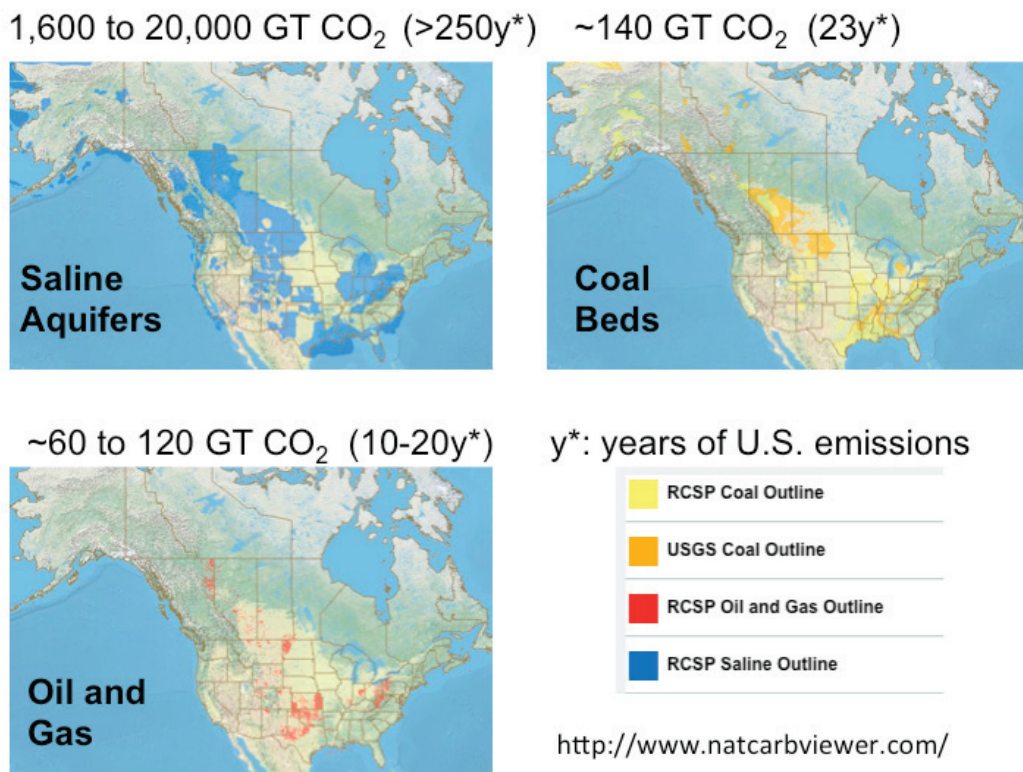


FIGURE 3.7 U.S. CO₂ sequestration capacity estimates for various geological reservoirs. Saline aquifers have the highest potential for CO₂ sequestration, followed by depleted coal beds and oil and gas fields. SOURCE: Created using NATCARB, <http://www.natcarbviewer.com/>.

in North America. The Benson et al. (2012) review emphasizes the need for research, geological assessments, and—even more crucial to the viability of sequestration—commercial-scale demonstration projects for improvement of confidence in capacity estimates.

Current annual rates of CO₂ sequestration from existing projects are small compared to the amount required to make a significant change to atmospheric CO₂ concentrations. The current scale of CCS is on the order of millions of tons of CO₂ per year, with four large-scale CCS projects in place totaling ~50 MtCO₂ sequestered and demonstrated monitoring sufficient to ensure efficacy of the injected CO₂. These projects

have been operating from a few years to almost two decades, thereby demonstrating the effective and safe deployment of CCS (Benson et al., 2012).²²

However, it is important to recognize that the scale required for adequate CO₂ sequestration to significantly reduce negative climate change impacts is much greater. Nine additional projects are under construction and are expected to be operational by 2016, with an estimated 13 MtCO₂ stored per year. The IEA CCS Roadmap (IEA, 2013b) reports that in order for CCS to make up 17 percent of the CO₂ mitigation portfolio through 2050, the scale of CCS needs to increase from the order of millions of tons of CO₂ per year to ~7 GtCO₂/yr (Global CCS Institute, 2013; IEA, 2013b).

Important considerations include the long-term integrity of the cap rock and other qualities of the reservoir that minimize leakage, and, due to the large net volumes of injected fluids needed, the risk of inducing seismic events through overpressurizing the reservoir (NRC, 2013a). With nearly 40 years of experience from EOR, a great deal of information has been gained associated with the safe subsurface injection of CO₂ (Benson et al., 2012). A recent study by Gan and Frohlich (2013) suggests that supercritical CO₂ injection since 2004 in the Cogdell oil field north of Snyder, Texas, may be a contributing factor to seismic activity taking place between 2006 to 2011, with a total of 18 earthquakes having magnitudes of 3 or greater. Zoback and Gorelick (2012) state that the injection of large volumes of CO₂ into the brittle rocks commonly found in continental interiors will likely trigger seismic events, which could subsequently affect seal integrity, thereby increasing the potential for CO₂ leakage. These recent studies highlight the importance of ongoing research in the field of CO₂ sequestration in geological reservoirs if CDR methods such as BECCS and DACS are to move forward and contribute significantly to reducing negative impacts of climate change.

As shown in Figure 3.8, the leakage probability generally decreases over time from secondary trapping mechanisms, such as solubility trapping due to dissolution of supercritical CO₂ into saltwater (brine) already present in the porous rock. In addition, given the higher density of the saltwater containing dissolved CO₂ compared to the surrounding fluids, the mixture will sink to the bottom of the formation over time, further trapping CO₂. Over even longer timescales, mineral trapping may take place due to the formation of carbonic acid in the reservoir. Over time, this weak acid can react

²² It should also be noted that the U.S. Department of Energy already has in place a number of key carbon capture and sequestration research programs and initiatives in place under the Office of Fossil Energy (OFE). More specifically, the OFE allocated \$1.52 billion of the \$3.4 billion it received from the Recovery Act in 2009 for a competitive solicitation of industrial carbon capture and energy efficiency improvement projects, including for innovative concepts for beneficial reuse of CO₂. Three projects chosen are aimed at testing large-scale industrial CCS, expected to capture 6.5 MtCO₂ per year by the end of September 2015. Further information can be found at <http://energy.gov/fe/office-fossil-energy>.

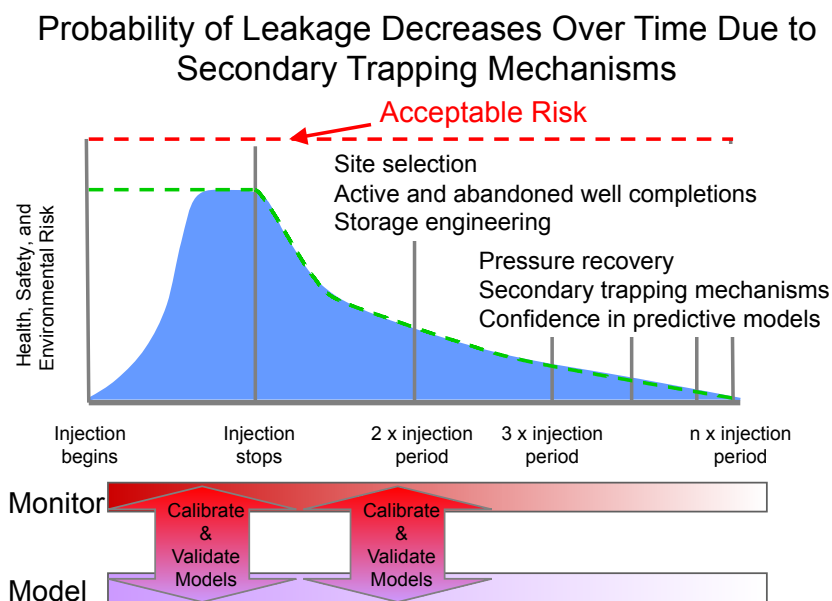


FIGURE 3.8 Evolution of health, safety, and environmental risk over time. Leakage generally decreases over the lifetime of the CO₂ sequestering activity. SOURCE: GEA, 2012.

with minerals in the rock, leading to the formation of carbonate minerals in which the CO₂ is chemically transformed and, hence, more permanently trapped.

A study by Hepple and Benson (2005) was carried out that discusses the performance requirements and implications of surface seepage. Figure 3.9 (left) from this study compares allowable emissions for stabilization of carbon dioxide concentrations at 550 parts per million by volume (ppmv) and expected emissions for different leakage rates as a function of time. This assumes that carbon sequestration is the only mitigation measure used to reduce CO₂ emissions below a particular reference scenario (IPCC SRES scenario A1B), which results in the sequestration of about 10,000 GtCO₂ over a period of 300 years. In this case, leakage rates below 0.1 percent of sequestered CO₂ lead to emissions less than those that are allowable for stabilization. However, from Figure 3.9 (right), an annual leakage rate of 0.1 percent of stored CO₂ leads to only ~40 percent of the CO₂ stored after 1,000 years, while a leakage rate of 0.01 percent leads to ~90 percent stored over 1,000 years.

The cost of geological sequestration includes the site characterization, capital costs (i.e., well surface equipment, drilling costs, and additional CO₂ compression in some in-

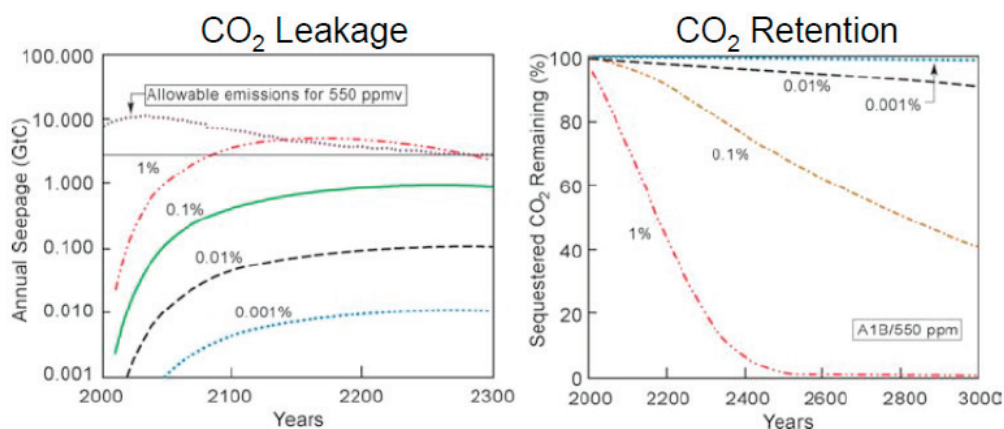


FIGURE 3.9 Comparison between “allowable” and expected emissions (left) and percent stored CO₂ remaining (right) for different leakage rates as a function of time. SOURCE: Hepple and Benson, 2005.

stances), operating and maintenance, monitoring, and verification. Benson et al. (2012) estimate that CCS has the potential of increasing the cost of electricity generation by 50 percent to 100 percent, with capital costs and parasitic energy requirements of 15 percent to 30 percent being the substantial cost drivers. The reservoir characterization costs are less expensive in the case of oil and gas formations compared to saline aquifers or deep coal seams because oil and gas sites were previously characterized from exploration efforts. The cost of characterization will also depend on the aerial extent of the potential CO₂ migration plume, which may be determined by regulations (Rubin et al., 2007). The costs associated with drilling primarily depend on the number of wells, including those for produced water as required, field injectivity, and the allowed overpressure. Operating and maintenance costs are expected to be comparable to the costs of water injection for secondary oil recovery processes (Bock et al., 2003; Rubin et al., 2007). Monitoring costs are expected to be a small fraction of the overall costs (Benson et al., 2004). According to the International Energy Agency (IEA, 2009), the potential global investment required solely for CO₂ sequestration for stabilization of atmospheric CO₂ to 450 ppmv ranges between \$0.8 to \$6 billion in 2020 and \$90 to \$600 billion in 2050.²³ More specifically, the costs associated with existing CO₂ sequestration projects are \$11/tCO₂ to \$17/tCO₂ for the project at Sleipner (North Sea), \$20/tCO₂ for the one at Weyburn (Saskatchewan), and \$6/tCO₂ for the one at In Salah (Algeria) (ITFCCS, 2010). If CO₂ is used for EOR, the revenues from the additional gas and

²³2009 U.S. dollars.

oil produced will reduce the cost of CO₂ disposal, but in these cases the majority of the CO₂ is recovered and reused. The purchase price of CO₂ is about \$40/tCO₂ to \$50/tCO₂ for EOR operations (Benson et al., 2012).

Benson et al. (2012) emphasize that environmental risks of geological sequestration appear manageable, but regulations will be required to govern site selection, operating guidelines, and the monitoring and closure of a sequestration facility. Public perception of the safety and effectiveness of geological sequestration will likely be a challenge until more projects are under way with an established safety record.

In addition to geological sequestration, CO₂ can also be injected into the mid-depth ocean (i.e., 1,000 to 3,000 m deep; see Figure 3.10). Within this approach, the CO₂ is stored on the order of hundreds to thousands of years before it returns to the atmosphere through ocean circulation. Alternatively, there is deep-injection ocean disposal,

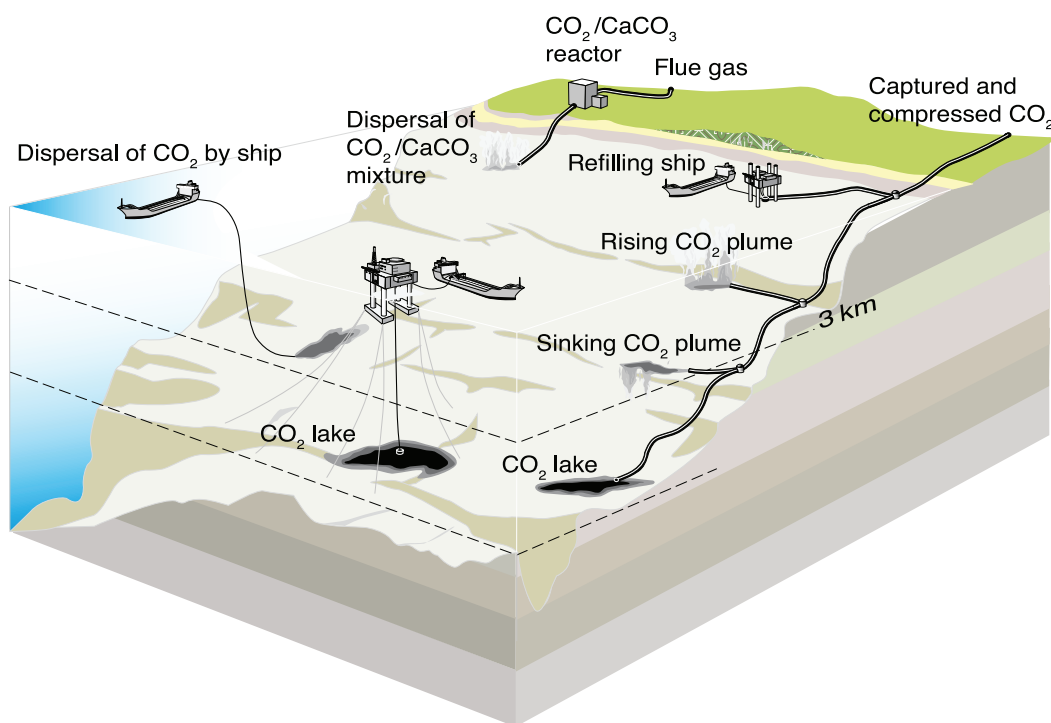


FIGURE 3.10 Ocean disposal strategies for inorganic processes (i.e., not ocean fertilization). CO₂ could potentially be placed in the ocean either as a highly compressed gas (CO₂), or dissolved in alkalinity-enriched seawater (CO₂/CaCO₃). Highly compressed CO₂ could be placed on the seafloor or dispersed in plumes. Pipes or ships could be used to transport the CO₂. CO₂ and alkalinity-enriched seawater would need to be dispersed in the ocean. SOURCE: IPCC, 2005, Chapter 6 on Ocean Storage.

in which stationary pools of CO₂ are created near the bottom of the ocean, with a potential sequestration capacity on the order of 1,000 GtCO₂ (IPCC, 2005). Due to the potential biological impacts, high cost, sequestration reversibility, and public acceptance concerns, little research is being conducted on ocean sequestration of CO₂ today.

CO₂ could potentially be stored in the ocean in a form where the CO₂ acidity is neutralized in solution by the addition of alkalinity derived by carbonate (IPCC, 2005; Rau, 2011; Rau and Caldeira, 1999) or silicate minerals (Kirchofer et al., 2012). It has been proposed that such solutions could be added to the ocean (Figures 2.1 and 3.10). These alkaline and CO₂-enriched waters would bring ocean pH and the carbonate mineral saturation state back closer to preindustrial values, offsetting at least some of the ocean acidification caused by excess CO₂, and thus might be expected to have a positive effect on marine calcifiers (NRC, 2010b; Rau et al., 2012). However, these approaches require a substantial mining infrastructure and large volumes of inflowing water, so there is potential for substantial local adverse environmental consequence. Economic considerations indicate that application of these approaches, if they can be cost competitive, would largely be limited to coastal environments with co-located availability of concentrated CO₂ streams, carbonate or silicate minerals, and ocean water (Rau and Caldeira, 1999).

A hybrid sequestration scheme has been proposed (Schrag, 2009) in which CO₂ is injected under a thin layer of sediments at the ocean's floor to combine aspects of geological sequestration with ocean sequestration. A related hybrid scheme is to inject CO₂ into deep-sea basalt reservoirs, such as the Juan de Fuca plate (Goldberg et al., 2008; Marieni et al., 2013). Another concept involves the displacement of methane from methane hydrate structure with CO₂, which could potentially enhance methane production with the co-benefit of CO₂ sequestration (Ohgaki et al., 1996). The hybrid and methane displacement in hydrates approaches are still at the very early research stages.

Looking forward, the committee identified a couple of important future research directions for CO₂ sequestration:

- Rapid expansion and scale-up of CO₂ sequestration demonstration projects with monitoring to gain experience, improve procedures, and increase public understanding of the safety of the process; and
- Increased research focus on reservoir quality and capacity to ensure safety and efficacy; all sequestration reservoirs are unique and require dedicated characterization.

The technical readiness of CO₂ sequestration is at the intermediate stage since prototypes already exist, but not at the required scale for significant CO₂ sequestration, i.e., on the order of tens of gigatonnes CO₂ per year. Although efforts have been made to monitor the CO₂ leakage for the operations currently in practice at the scale of millions of tons of CO₂ per year, it is still uncertain whether the CO₂ will be stored on the order of millennia. Additional monitoring and leakage studies need to be carried out. The environmental impacts of CO₂ sequestration may be considered medium given the potential of induced seismicity and Earth's unknown response to long-term CO₂ mineralization sequestration. Although studies by Benson et al. (2012) and Dooley (2013) show significantly high capacity estimates for geologic sequestration of CO₂, this does not indicate the timescale of allowable injection. Based on the required projections to limit 2°C warming from the IEA Roadmap (IEA, 2013b), the required annual progress in CO₂ sequestration is significant, with 1 GtCO₂/yr up to 2025, ~8 GtCO₂/yr to 2050, and up to ~20 GtCO₂/yr through 2100. These projects result in ~800 GtCO₂ cumulatively sequestered up to 2100. Costs of CO₂ sequestration range from \$10/tCO₂ to \$20/tCO₂ (ITFCCS, 2010).

Utilization of Carbon Dioxide and Available Markets

The primary market for CO₂ today is EOR. Although the food beverage industries and chemical markets exist for CO₂, they do so to a lesser extent than EOR. In the United States, ~54 MtCO₂/yr is used for EOR and most of the CO₂ is sourced naturally rather than anthropogenically. In particular, 80 percent of the CO₂ is sourced from natural reservoirs, while the remaining is from anthropogenic source (Kuuskraa et al., 2013). According to Advanced Resources International (2011), state-of-the-art and “next-generation” EOR in the United States have a long-term total capacity of 10 and 20 GtCO₂, respectively. In addition to EOR, ~80 to 120 MtCO₂/yr is sold commercially for various applications, primarily including chemical solvent production, coffee decaffeination, fertilizer production, and carbonated beverages. The CO₂ demand for refrigerants and solvents is less than 1 MtCO₂/yr, while the beverage industry is on the order of ~8 MtCO₂/yr. Although EOR has the potential to involve some degree of permanent CO₂ sequestration, it is important to note that most utilization methods ultimately return CO₂ into the atmosphere (Global CCS Institute, 2013; IPCC, 2005).

In the section Accelerated Weathering and Mineral Carbonation, the transformation of CO₂ with alkalinity to form stable or dissolved carbonates was reviewed. These options could potentially store CO₂ in useful or marketable forms. A limitation of solid carbonate sequestration is the relatively small size of available markets for solid carbonates, which primarily include road building and concrete. Consideration of the current ag-

gregate market provides a reasonable estimate on the potential impact of this utilization option, which is small (on the order of less than 1 percent of emissions) and was discussed in greater detail previously. A study by Sridhar and Hill (2011) estimated that replacing 10 percent of building materials with carbonate minerals has the potential to reduce CO₂ emissions by 1.6 Gt/yr. If there is at some point in the future a market for substances that help reduce ocean acidification (NRC, 2010a), there could conceivably be a market for the high-alkalinity, CO₂-rich solutions that could be generated by accelerated weathering processes.

Looking forward, the committee identified several important future research directions for utilization of CO₂:

- Catalyst design for CO₂ conversion processes with reduced energy; and
- Advanced uses of CO₂ that can expand capacity and verify permanent sequestration of CO₂ without re-release into the atmosphere, for example, monitored EOR, monitored enhanced natural gas recovery, geothermal heat recovery, waterless fracking, carbonate formation, or use of high-alkalinity high-CO₂ solutions to counter ocean acidification.

CHAPTER SUMMARY

Some of the methods listed in Table 2.2 are both affordable and benign, while some may be benign but costly in the near term. For instance, land management methods including reforestation and afforestation, water management, low- or no-till agriculture, and cover crop agriculture have the potential to store ~2 to 5 GtCO₂/yr at a cost of ~\$1/tCO₂ to \$100/tCO₂ (see Table 2.2). Today, the upper range of these estimates equates to just over 10 percent of global CO₂ emissions. Specifically, tropical afforestation accounts for over half of this potential sequestration (Smith and Torn, 2013) and is based on land and resource availability. It is important to consider the potential scale of methods, even if they are affordable and benign, to determine whether they can reasonably contribute to a portfolio of responses to the CO₂ problem.

Another strategy of significant impact with reasonable costs is the concept of bioenergy. In this process, biomass may be directly combusted or co-fired with coal or natural gas to produce process heat or electricity. The generation of a variety of outputs (i.e., polygeneration) such as electricity, process heat, fuel, and chemicals is also possible through gasification of the biomass, which results in the production of synthetic gas (i.e., CO + H₂), allowing for product synthesis flexibility dependent on market potential. However, without separation of CO₂ from the flue (combustion) or fuel (gasification) gas, this process is not a negative-emissions strategy. Therefore, CO₂ separation

and subsequent sequestration are required for BECCS to be capable of CDR. From the perspective of reducing the growth of atmospheric CO₂ levels, employing BECCS has the same impact as the comparable amount of CCS and bioenergy being deployed until such time as fossil fuel emissions are minimal, which is unlikely to occur on any large scale for decades. Very similar to conventional CCS, the CO₂ separation costs are in line with CCS at ~\$100/tCO₂. BECCS has the theoretical potential to remove up to 18 GtCO₂/yr; however, this removal rate would require ~1,000 million acres of arable land for biomass cultivation, which represents nearly three-quarters of the planet's available arable land, and thus is not realistic under any plausible scenario. Therefore, depending on world population and competition for land for food production and urban expansion, the level of CDR impact from BECCS is likely to be dramatically lower than the theoretical potential might suggest.

Although both capture and sequestration are inherent within those approaches that increase terrestrial carbon stocks, this is not the case for bioenergy. Hence, application of BECCS on an annual basis may also be limited by the sequestration potential. Geologic sequestration is currently practiced on the order of millions of tons of CO₂ per year. (Other concepts, such as accelerated weathering approaches, have not yet progressed beyond benchtop scale.) IEA and World Energy Outlook roadmaps indicate that through 2050 this scale needs to be on the order of gigatonnes of CO₂ per year if warming beyond 2°C is to be avoided. However, this requires a thousandfold increase in the current sequestration activity and the construction and operation of hundreds to thousands of individual sources and injection sites. Although theoretically this large number of sources and injection sites is possible (IEA, 2005), to be technically feasible at this scale will require additional demonstration and pilot plants to be brought on-line very soon. In addition to the existing four projects globally, another nine projects are under construction today, with the potential to capture and store 13 MtCO₂/yr, and should be operational by 2016 (IEA, 2013b). Again, this scale will have to increase by at least an order of magnitude to achieve any significant impact on net carbon emissions.

Although the scales of utilization are limited, it is important to consider their potential. Due to the immense scale of CO₂ to be captured, some types of CO₂ utilization will undoubtedly make up part of the portfolio of responses for preventing rerelease of CO₂ into the atmosphere in addition to geologic sequestration. For instance, another option may be to produce carbonate minerals by reacting CO₂ with available alkalinity. The carbonate may be used as "synthetic" aggregate for available construction markets. In addition, these carbonate minerals could potentially be left in dissolved form where they could be released into the ocean, thereby countering acidification caused by passive uptake of excess CO₂ from the atmosphere.

Overall, all of these options have trade-offs that are described in greater detail in the previous sections of this chapter. Land management approaches and BECCS are generally characterized by lower risk and lower costs, whereas ocean iron fertilization is generally characterized as higher risk and DACS as currently higher cost.

Tables 3.2 and 3.3 provide a quick summary overview of the committee's judgments on aspects such as effectiveness, technical readiness, ramp-up time, duration of effects, cost, ability to detect and monitor, and various risks of the CDR strategies presented in this chapter; aspects of capture and sequestration systems are discussed in the two tables, respectively. In each category, the committee has provided an estimate of not only the magnitude of the effect (e.g., high, medium, low, and what those categories mean for that table entry), but also the committee's confidence in that categorization. The entries in the tables are the product of committee deliberation based on an understanding of the available literature. Although capture from point-source emitters coupled to sequestration (i.e., CCS) is not considered a CDR technology, it is included in Table 3.2 for comparison with the CDR technologies considered in this report.

CDR Summary Table 3.2 CO₂ Capture Approaches

Committee Confidence:

● High ● Medium ○ Low

Point-Source Capture	Direct Air Capture	Biological Land Based	Biological Ocean Based	Accelerated Weathering Land Based	Accelerated Weathering Ocean Based
Fuel/fuel gas		Afforestation, soil, land management	Ocean iron fertilization		
NOTES:					
Technological readiness, speed to deployment, technical risk					
Mature technology (ready to deploy quickly, low technical risk): technology exists at scale					
Intermediate maturity technology: prototypes exist, not to scale					
Immature technology (not ready to deploy quickly, high technical risk): needs prototyping... ..					
Time required to scale to maximum deployment with major effort, achieving significant capture rate (~1 GtCO₂/yr)					
Fast: years (i.e., < 10 yr)					
Medium: decades (i.e., 10 < x < 30 yr)					
Slow: many decades (i.e., > 30 yr)					

Effect per unit cost for pilot scale with currently available technology

High: dollars per ton CO₂ (i.e., <\$10/tCO₂)

Medium: tens of dollars per ton CO₂ (i.e., \$10/tCO₂ < x < \$100/tCO₂)

Low: hundreds of dollars per ton CO₂ (i.e., >\$100/tCO₂)



Maximum feasible deployment capture rate

High: >10 GtCO₂/yr (i.e., >30 percent of current emission rate; order of magnitude of current emission rate)

Medium: 1 < x < 10 GtCO₂/yr (i.e., order 10 percent of current emission rate)

Low: < 1 GtCO₂/yr (i.e., order 1 percent of current emission rate)



Verifiability: Ability to confirm that capture has happened and quantify how much CO₂ has been captured

Easily verifiable: existing and planned observation systems can verify without retasking

Moderately easy to verify: existing observation systems would need retasking or known technology would need to be deployed

Difficult to verify: new technology or methods would need to be developed or deployed



Table 3.2 Continued

Point-Source Capture	Direct Air Capture	Biological Land Based	Biological Ocean Based	Accelerated Weathering Land Based	Accelerated Weathering Ocean Based
		Afforestation, soil, land management	Ocean iron fertilization		
Fuel/fuel gas					
NOTES:					
Negative environmental consequences					
Minor: mostly local impacts; can be mitigated consistent with current national environmental protection standards					
Medium: potentially serious impacts that may be difficult to mitigate to current environmental protection standards					
Major: severe national or global impacts incompatible with current environmental protection standards; impacts may exceed environmental benefits of climate change mitigation					

Environmental co-benefits

High: numerous and/or very likely co-benefits, such as protection of watersheds from erosion, wildlife habitat and diversity, recreational opportunities, or reduction in ocean acidification

Medium: modest or uncertain co-benefits

Low: very few or no co-benefits



Sociopolitical risks (include national security)

Minor: limited and mostly local economic and social impacts

Medium: potential for serious national or regional economic, social, political, or security impacts that may be difficult for governments to manage

Major: potential for severe national and regional economic hardship, social dislocation, political instability, and civil or military conflict

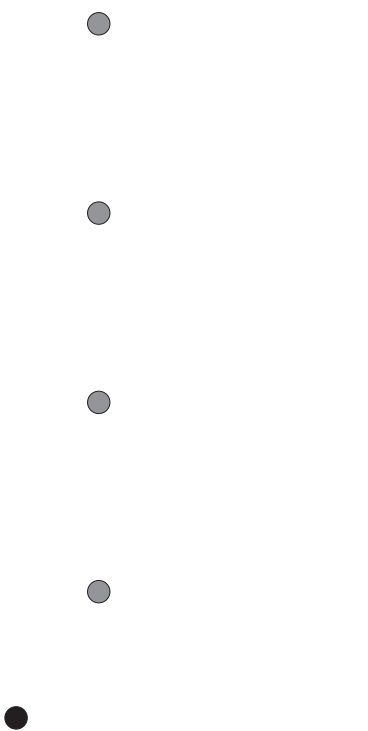


Table 3.2 Continued

	Point-Source Capture	Direct Air Capture	Biological Land Based	Biological Ocean Based	Accelerated Weathering Land Based	Accelerated Weathering Ocean Based
NOTES:	Fuel/fuel gas		Afforestation, soil, land management	Ocean iron fertilization		
Governance challenges for deployment at scale						
No novel governance challenges	●	●	●			
Governance challenges likely to be primarily territorial, but with some legitimate interest by other states					●	
Potential for substantial adverse effects across international borders or to an international commons				●		●
Risk of detrimental deployment from unilateral and uncoordinated actors						
Low risks: few actors (individuals, groups, nations) have large enough resources to deploy technique and motivation to do so	●	●	●		●	●
Medium risks				●		
High risks: many actors with resources and motivation						

CDR Summary Table 3.3 CO₂ Sequestration Approaches

Committee Confidence:

● High ● Medium ○ Low

Reduced Carbon (e.g., land plants, biochar)	Oxidized Carbon Sequestered as Molecular CO ₂ in Solid Earth (geologic)	Oxidized Carbon Sequestered as Molecular CO ₂ in Ocean	Oxidized Carbon Sequestered in Other Compound Form (e.g., CaCO ₃)	Oxidized Carbon Sequestered in Ocean
Land management	For example, as part of CCS, BECCS, or DACS	Ocean iron fertilization	Accelerated weathering on land	Accelerated weathering in or near ocean

NOTES:

Technological readiness, speed to deployment, and technical risk

Mature technology (ready to deploy quickly, low technical risk): technology exists at scale ●

Intermediate maturity technology: prototypes exist, not to scale ●

Immature technology (not ready to deploy quickly, high technical risk): needs prototyping ●

Time required to scale to maximum deployment with major effort

Fast: years (i.e., <10 yrs)

Medium: decades (i.e., 10 < x < 30 yr) ●

Slow: many decades (i.e., >30 yr)

continued

Table 3.3 Continued

	Reduced Carbon (e.g., land plants, biochar)	Oxidized Carbon Sequestered as Molecular CO ₂ in Solid Earth (geologic)	Oxidized Carbon Sequestered as Molecular CO ₂ in Ocean	Oxidized Carbon Sequestered as Other Compound (e.g., CaCO ₃), Solid Form	Oxidized Carbon Sequestered in Ocean
	For example, as part of CCS, BECCS, or DACS		Ocean iron fertilization	Accelerated weathering on land	Accelerated weathering in or near ocean
NOTES:	Land management	DACS			
Persistence (sequestration lifetime)					
Millenia		●		●	●
Centuries	●		●		
Decades					
Maximum sequestration amount					
High: >10,000 GtCO ₂ (i.e., >30 percent of fossil fuel resource, order 100 percent of fossil fuel resource)		●		●	●
Medium: 1,000 < x < 10,000 GtCO ₂ (i.e., order 10 percent of fossil fuel resources)					
Low: order <1,000 GtCO ₂ (i.e., order 1 percent of fossil fuel resources)	●		●		

Verifiability: Ability to detect and quantify the rate at which CO₂ was captured and added to the sequestration reservoir

Easily verifiable: existing and planned observation systems can verify without retasking	●	●
Moderately easy to verify: existing observation systems would need retasking or known technology would need to be deployed	●	●
Difficult to verify: new technology or methods would need to be developed or deployed		

Verifiability: Ability to detect and quantify the rate at which CO₂ is leaking out of the reservoir

Easily verifiable: existing and planned observation systems can verify without retasking	●	
Moderately easy to verify: existing observation systems would need retasking or known technology would need to be deployed	●	○
Difficult to verify: new technology or methods would need to be developed or deployed		●

continued

Table 3.3 Continued

Reduced Carbon (e.g., land plants, biochar)	Oxidized Carbon Sequestered as Molecular CO ₂ in Solid Earth (geologic)	Oxidized Carbon Sequestered as Other Compound (e.g., CaCO ₃), Solid Form	Oxidized Carbon Sequestered in Ocean
Land management	For example, as part of CCS, BECCS, or DACS	Accelerated weathering on land	Accelerated weathering in or near ocean
Verifiability: Ability to quantify increase in carbon stocks of the sequestration reservoir (i.e., verification of change in carbon mass stored)			
Easily verifiable: existing and planned observation systems can verify without retasking	●	●	
Moderately easy to verify: existing observation systems would need retasking or known technology would need to be deployed	●	●	●
Difficult to verify: new technology or methods would need to be developed or deployed			
Negative environmental consequences			
Minor: mostly local impacts; can be mitigated consistent with current national environmental protection standards			

- Medium: potentially serious impacts that may be difficult to mitigate to current environmental protection standards ○
- Major: severe national or global impacts incompatible with current environmental protection standards; impacts may exceed environmental benefits of climate change mitigation ○

Sociopolitical risks (include national security)

- Minor: limited and mostly local economic and social impacts
- Medium: potential for serious national or regional economic, social, political, or security impacts that may be difficult for governments to manage
- Major: potential for severe national and regional economic hardship, social dislocation, political instability, and civil or military conflict

continued

Table 3.3 Continued

	Reduced Carbon (e.g., land plants, biochar)	Oxidized Carbon Sequestered as Molecular CO ₂ in Solid Earth (geologic)	Oxidized Carbon Sequestered as Molecular CO ₂ in Ocean	Oxidized Carbon Sequestered in Other Compound (e.g., CaCO ₃), Solid Form	Oxidized Carbon Sequestered in Ocean
NOTES:		For example, as part of CCS, BECCS, or DACS	Ocean iron fertilization	Accelerated weathering on land	Accelerated weathering in or near ocean
Governance challenges for deployment at scale					
No novel governance challenges	●	●			
Governance challenges likely to be primarily territorial, but with some legitimate interest by other states				●	●
Potential for substantial adverse effects across international borders or to an international commons			●		

Social Context

Carbon dioxide removal (CDR) approaches generally share some characteristics with respect to how they are perceived by society. Some methods, such as direct air capture and sequestration (DACs) and reforestation, result in far less of a perturbation to the Earth system than that associated with albedo modification (see companion report *Climate Intervention: Reflecting Sunlight to Cool Earth*). Deployment of such methods is more likely to be viewed as an “undoing” of what has been done and, thus, may be perceived as more benign. Moreover, these approaches act slowly, allowing some time to assess the impacts and either adapt or cease deployment on more land or the activity itself prior to the occurrence of possible significant negative secondary effects. These characteristics—the undoing, the opportunity to assess as things evolve, and the ability to stop—define the social context under which such measures are deployed.

Overall, the basic concept of removing CO₂ from the atmosphere is relatively uncontroversial, especially in comparison to albedo modification (see companion report). The primary exceptions are proposals to fertilize the ocean with iron or other micronutrients (see Ocean Iron Fertilization in Chapter 3), which raise legal and ethical concerns, and various land management techniques, which raise political and social issues related to the competition for land use. Last, economic considerations are important for all of the CDR approaches discussed in this volume.

LEGAL AND ETHICAL ISSUES

Ocean iron fertilization directly manipulates the base of the ocean food web in order to stimulate the growth of phytoplankton to enhance carbon uptake and, as such, is of concern from both legal and ethical perspectives. The implications for the health of the marine ecosystem are not well known and could potentially be substantial on regional scales, both ecologically and economically. To a lesser extent, proposals for accelerated weathering in the ocean also raise questions concerning the potential impacts on ocean ecosystems due to the possibility of large volumes of material to be disposed of in the ocean.

Legally, under the international treaties of the London Protocol and London Convention, dumping of wastes into the ocean is forbidden. The International Convention

on Biological Diversity requested that its own parties “ensure that ocean fertilization activities do not take place until either there is adequate scientific basis on which to justify such activities or the activities are small-scale scientific research studies within coastal waters” (Bracmort and Lattanzio, 2013; CBD, 2010).

Overall, there are ethical concerns over the use of the ocean as a dumping ground. There have already been examples of an iron fertilization experiment that has been temporarily blocked by nongovernmental organizations to prevent “dumping” of iron in the Southern Ocean (Schiermeier, 2009a,b), as well as controversy surrounding the actions of a unilateral and uncoordinated activity that involved experimenting with ocean fertilization in the Northern Pacific (see Box 2.1).

Ethical issues for the other CDR techniques described in this volume are generally of much less concern since there is generally less direct interference with local or regional environmental conditions, and the considerations are about the practical matters for most of these CDR techniques. These techniques produce a slow response, so the effects of climate change will continue to increase before they lessen, and nations that are engaged in such practices may have to deal with perceptions of their futility, posing challenges to sustained long-term deployment.

POLITICAL AND SOCIAL CONSIDERATIONS

Among CDR approaches, there are differing social implications as well as different perceptions. Land management approaches—including afforestation, reforestation, and bioenergy production—have the potential to initiate debates over land use. This is especially true regarding the clearing of areas that are currently in native vegetation or are used for agricultural production for the purpose of growing bioenergy crops. These debates include the “food versus fuel” dilemma, in particular for corn-based ethanol (Ayre, 2007; Babcock, 2011; Grundwald, 2008; Wilson, 2008). The CDR approaches that involve geological sequestration generally involve limited public perception issues (Mabon et al., 2013). Nevertheless, they are subject to the same environmental and safety risks posed by carbon capture and dequstration (CCS) (leakage, seismic activity, and water contamination; see Geological Sequestration) and therefore are not without political, social, legal, and ethical implications.

ECONOMIC CONSIDERATIONS

As described in Chapter 3, many of the barriers to implementation of CDR approaches are in large part driven by economics and effectiveness. In addition, the slowly acting

nature of these measures, and the need for their deployment to be large scale in order to be effective relative to the global climate, bring about an additional social consideration: determining how the burden and cost of deployment will be shared. Arguments employed today against reducing our domestic fossil fuel consumption often focus on the burden that would be absorbed by the United States or the vast majority of people yet to share in the benefits of modern society, and the perceived futility of any national program, as long as other nations—like China and India—continue to burn fossil fuels at high rates. Similar perceptions will likely be the case with CDR. Because it is slow acting, substantive change on the timescales of interest (i.e., decades) will require adoption of CDR techniques on the international scale. The social context is less about understanding how one set of actions affects the global climate or large numbers of people in the short term and more about how to mobilize multiple nations to engage in a coordinated effort. Such action requires each participating country to make a sacrifice or investment (depending mainly on how the challenge is perceived or framed) for a lower-carbon future, similar to what is required to reduce fossil fuel emissions.

In the 2009 Copenhagen Accord, parties agreed that in order to prevent dangerous anthropogenic interference with the climate system, the increase in global average temperature should be limited to less than 2°C (UNFCCC, 2009). It has been estimated that limiting cumulative greenhouse gas emissions to 1,000 GtCO₂ equivalent (eq) would lead to a 25 percent probability of global warming exceeding 2°C, while a cumulative limit of 1,440 GtCO₂ would lead to a 50 percent probability of warming beyond 2°C (Allen et al., 2009; Meinshausen et al., 2009). The corresponding stabilization scenario developed by the IPCC, RCP2.6 (Figure 1.1), has total emissions of about 1,600 GtCO₂-eq from 2000 to 2100. For comparison, business-as-usual scenarios (scenarios that do not assume additional policy action to reduce emissions) forecast 2,500 to 4,000 GtCO₂-eq from 2000 to 2050, and 4,600 to 7,300 GtCO₂-eq from 2000 to 2100. Thus, limiting warming to 2°C will require CO₂ emissions reduction, postemissions consumption by CDR, or some combination of these in the amounts of roughly 1,000 to 3,000 GtCO₂ before 2050, and 3,000 to 6,000 GtCO₂ before 2100.

CDR approaches present opportunities to address the excess levels of CO₂ in the atmosphere, but there are limitations to these approaches that must be overcome if they are to be implemented widely. In particular, implementation of bioenergy with carbon capture and sequestration (BECCS) and/or DACS on a large scale depends on the relationship between cost of deployment and effective price on carbon emissions, which could be imposed either directly (e.g., with a tax or via cap-and-trade mechanism) or indirectly (e.g., with performance standards). Although the committee does not advocate for any specific policies related to carbon emissions, we note that poli-

cies (or lack thereof) are an important part of the economic calculations for determining the viability of various CDR approaches.

Integrated assessment models (IAMs) are common tools for—among other things—evaluating the potential role of CDR techniques in the various climate change mitigation scenarios, as they include many of the interconnected complexities such as climate and atmospheric modeling, agriculture and land use, and various technologies to be implemented with their related economics (Kriegler et al., 2013). Of the CDR strategies considered in this report, BECCS is the most commonly incorporated in the IAMs.¹ In many of the scenarios examined by IAMs, for stabilization of atmospheric greenhouse gases CO₂-equivalent (CO₂-eq) atmospheric concentrations at a reduced level of 450 ppm, abatement cost is greatly reduced with the inclusion of BECCS.² For example, Edmonds et al. (2013) report that to limit radiative forcing to 2.6 W/m² and meet the 450-ppm CO₂-eq target by 2100 requires carbon prices of \$16/tCO₂ in 2020, rising to \$620/tCO₂ in 2095; this scenario is driven by the availability of technological options for CDR, which are time dependent, with a greater number of options available in the near term.³ Although the exact price estimates are likely to be highly uncertain, a general lesson learned from these IAM studies is that projected carbon prices are about three times higher if BECCS and DACS are not available.

In the case of delayed action along one of the climate change mitigation trajectories, costs increase significantly. The study by Kriegler et al. (2013) reports similar carbon prices with an estimated 5 percent annual rate of increase; for the various scenarios considered, they estimated a near-term price of between \$10/tCO₂ and \$50/tCO₂, rising to \$500/tCO₂ to \$2500/tCO₂ in 2100. Azar et al. (2010) estimate that it may take half a century for the technological and social infrastructure for practical and cost-effective BECCS to exist, to be applied at a global scale, and to reduce atmospheric carbon dioxide concentrations at a significant rate (e.g., 0.5 to 1 ppm CO₂/yr, or 8 to 16 GtCO₂/yr⁴).

¹ It is important to note that bioenergy and CCS, coupled as BECCS, does not require these two components to take place in the same geographic region. If bioenergy and CCS efforts are taking place, the result is the same as BECCS efforts.

² The level of 450 ppm CO₂ will likely lead to an equilibrium warming of greater than 2°C (NRC, 2011). For reference, by the end of 2012, atmospheric concentrations of CO₂-eq had already reached 476 ppm (<http://www.esrl.noaa.gov/gmd/aggi/aggi.html>).

³ Future options will be limited by available land and pressures from an increased population; for further discussion of these issues, see Chapter 3.

⁴ The amount of CO₂ that must be captured and stored in order to reduce the amount of CO₂ in the atmosphere by one ton depends on emission scenarios and assumptions about the global carbon cycle. The committee uses a ratio of 2:1 for simplicity based on the fraction of CO₂ emissions that remain in the atmosphere under current conditions (see Table 2.1), but there are also positive feedbacks (e.g., release of CO₂ from permafrost) that may make this ratio higher (MacDougall, 2013).

In the analysis of Kreigler et al. (2013), BECCS is limited to a removal of $\sim 15 \text{ GtCO}_2/\text{yr}$;⁵ they conclude that if CDR were to be applied at sufficiently large scale, DAC would become economically competitive with BECCS due to land and resource limitations. Overall, the inclusion of BECCS into integrated assessment models allows for significantly lower targets to become possible at reduced costs.

It is important to emphasize that both BECCS and DACS, which are the CDR approaches that appear to have the greatest potential for carbon dioxide reduction given the current state of knowledge, depend on the availability of geologic reservoirs capable of accepting and reliably storing massive amounts of CO_2 (discussed in more detail in Chapter 3). Although the technology to capture CO_2 and sequester it in a geological reservoir exists today, significant improvements would be required for widespread deployment. Today there are five commercial-scale projects capturing and disposing of CO_2 at a combined rate of $\sim 5 \text{ MtCO}_2/\text{yr}$, with approximately 35 MtCO_2 sequestered since 1996 (Benson et al., 2012). According to the IAMs highlighted in the Special Issue on Science Policy of Negative Emissions Technologies in the journal *Climatic Change* (Tavoni and Socolow, 2013), the rates of future CDR range from 10 to $35 \text{ GtCO}_2/\text{yr}$. Meeting this challenge will require a thousandfold scale-up of the current CCS activities that take place today. CDR is at an early development stage, and further research and development and emerging technologies may greatly lower costs and increase capacity and deployment readiness and may thus significantly alter the above conclusions.

⁵ For reference, global integrated terrestrial primary production is approximately 220 GtCO_2 per year (Ciais et al., 2013; Field et al., 1998; MacDougall, 2013).

Way Forward

Climate change is one of the greatest challenges the world faces today. The rise of human societies has taken place during a stable period in the history of Earth's climate. Over the past 8,000 years Earth's climate maintained a relatively even balance with no large swings in the climate state (Petit et al., 1999) like those observed earlier in the paleoclimate record. Through the emissions of large amounts of greenhouse gases (GHGs) during the industrial age, humans have intervened in the planet's carbon cycle, shifting the equilibrium that existed for the bulk of human history. The carbon cycle itself is resilient and has feedback cycles that will allow it to return to an equilibrium (Zeebe and Caldeira, 2008), but those feedbacks operate over very long timescales—on the order of thousands of years.

Climate science has revealed that there are substantial risks to society posed by the large emissions of GHGs that have been and are continuing to be emitted into the atmosphere. These risks include not just warming, but threats from sea level rise, rapid ecosystem changes, ocean acidification, and extreme weather events (IPCC, 2013a,b, 2014a; NCA, 2014). Reducing the atmospheric burden of carbon dioxide (CO₂), the most prevalent and persistent GHG, is an essential component of reducing those risks. Returning the atmospheric concentration of CO₂ closer to the level that Earth had during the last several millennia as humans flourished on the planet would minimize risks for human societies that have grown to depend on the stability of Earth's climate.

Current emissions of GHGs by humans continue to push Earth further away from its historical climate state. Over the next few decades humans are likely to continue to emit large amounts of CO₂ to the atmosphere. Nevertheless, avoiding some of these emissions and/or removing some of that CO₂ from the atmosphere would slow this shift away from the historical state. Once anthropogenic emissions cease, it will take nature many thousands of years to remove enough of industrialized society's CO₂ emissions through natural processes such that they would no longer be of climatic concern. A more rapid return to lower CO₂ concentrations would involve removing CO₂ from the atmosphere. For now, while there are large sources of CO₂ emission, the avoidance of emissions from fossil energy sources through the use of improved energy efficiency, deployment of carbon-free energy sources (e.g., wind and solar power), carbon capture and sequestration (CCS), and carbon dioxide removal (CDR) techniques are all components of the portfolio of possible strategies for reducing the risks from climate change. For this report, the committee examined CDR techniques in the

context of both the present, with currently available technologies, as well as the future, as technologies and other solutions may evolve.

Even if CDR technologies never scale up to the point where they could remove a substantial fraction of current carbon emissions at an economically acceptable price, and even if it took many decades to develop even a modest capability, CDR technologies still have an important role to play. As described in the recent Intergovernmental Panel on Climate Change (IPCC) report, “[m]itigation scenarios reaching about 450 ppm CO₂-eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm to 550 ppm CO₂-eq in 2100. Depending on the level of the overshoot, overshoot scenarios typically rely on the availability and widespread deployment of BECCS and afforestation in the second half of the century” (IPCC, 2014a). Furthermore, since climate stabilization requires GHG emissions to be essentially zero, it is almost inevitable that some CDR will be needed in the long term to deal with residual emissions by nonparticipatory nations, or by sectors for which fossil fuel substitutes prove difficult to implement (e.g., aviation) (NRC, 2011a). Finally, after the time emissions finally do cease, even a modest amount of CDR, on the order of 1 GtCO₂/yr, can significantly shorten the time needed for CO₂ to recover to preindustrial values.

As discussed throughout this report, CO₂ removal from the atmosphere can be enhanced using a range of approaches from biological to chemical. To remove enough CO₂ from the atmosphere to offset a substantial fraction of today’s CO₂ emissions represents a major challenge given available technology and physical constraints (e.g., available land for growing bioenergy feed stocks, and disposing of sequestered CO₂). To take enough CO₂ out of the atmosphere to cause atmospheric concentrations to markedly decrease would be extraordinarily difficult. The challenge is to capture climatically important amounts of CO₂ out of the atmosphere, to sequester it reliably and safely, and to do this in a way that is economically feasible, environmentally beneficial, and socially, legally, and politically acceptable.

The committee has examined a number of CDR techniques through this lens throughout this report. There are land management activities, in particular preserving and restoring forests, that society can sensibly do at present that will help reduce CO₂ emissions, but not at the scale of current global CO₂ emissions. Bioenergy with carbon capture and sequestration (BECCS) exists today, but large-scale implementation will only become cost competitive in the coming decades and only differs in net atmospheric effect from the separate use of bioenergy and CCS when fossil fuel use is minimal, which is decades off at best. Accelerated mineral weathering on land or in the ocean may be technically feasible, but at substantial cost if done on the scale required

for achieving significant impact. Direct air capture and sequestration (DACs) has the theoretical potential to effectively sequester substantial quantities of CO₂ from the atmosphere provided nonfossil sources are used to power the separation of CO₂ from air, but it is unclear that this approach will be cost effective in the near term. Last, the environmental and sociopolitical risks of deploying ocean iron fertilization at a large scale would likely outweigh the potential benefits. Overall, there is value in pursuing multiple parts of a portfolio of these strategies, both for what can be done in the short term and what can be done in the long term.

SCALE

The scale of a system that removes a CO₂ molecule from the atmosphere and sequesters it reliably might be similar to the scale of the system that first put that CO₂ molecule into the atmosphere. Over the past decade, humanity has been emitting about 34,000,000,000 tons of CO₂ (34 GtCO₂) into the atmosphere each year (Table 2.1). Because there are more than 7,000,000,000 people (7 billion) in the world, this works out to about 5 tons of CO₂ per person per year, or about 30 pounds of CO₂ per person per day.¹ In 2010, the United States emitted about 20 tons of CO₂ per person per year²—about 110 pounds per American per day. For comparison, in 2012, Americans generated >4 pounds per person per day of municipal solid waste (i.e., trash or garbage).³ CO₂ is the waste we produce most prodigiously.

If CDR were to be used to avoid all climate change from U.S. CO₂ emissions, the United States would need to remove 110 pounds of CO₂ per day for each American. CO₂ is a dilute gas in the atmosphere, making up only about 0.04 percent of the atmosphere by volume (and about 0.06 percent by mass). This means that if we were able to remove 100 percent of the CO₂ molecules from a volume of air, we would need to process about 51,000 m³ (about 67,000 cubic yards) of air per American per day.⁴ This corresponds to a volume approximately 30 feet high (nearly 10 m) and the area of an American football field⁵ to be processed for each American each day. Nobody is suggesting that CDR will

¹ The committee is not suggesting that everyone on the planet is responsible for equal amounts of CO₂ emissions; this estimate is simply to help visualize the size of the challenge.

² See <http://data.worldbank.org/country/united-states>.

³ See <http://www.epa.gov/waste/nonhaz/municipal>.

⁴ The molecular weight of dry air is 28.97 g/mol and that of CO₂ is 44.01 g/mol. Therefore, if CO₂ is 400 ppm by volume (see Chapter 1), it is $400 \text{ ppm} \times 44.01 \text{ g/mol} / 28.97 \text{ g/mol} = 608 \text{ ppm}$ by mass. At sea level and 15°C, dry air is 1.275 kg/m³. Thus, 1 m³ of air contains $1.275 \text{ kg} \times 608 \text{ ppm} = 1.275 \text{ kg} \times 0.000608 \text{ kg CO}_2/\text{kg air} = 0.000775 \text{ kg CO}_2/\text{m}^3$. $50 \text{ kg of CO}_2 \text{ per American per day} = 50 \text{ kg CO}_2 / (0.000775 \text{ kg CO}_2/\text{kg air}) / (1.275 \text{ kg/m}^3) = 51,000 \text{ m}^3$.

⁵ See <http://www.nfl.com/rulebook>.

be the only tool used to reduce CO₂ emissions, but to make a substantial contribution reducing our net CO₂ emissions, CDR would need to be deployed at a substantive level.

These numbers indicate that, to make a substantive difference to the global climate, CDR would need to occur at a truly massive scale. Because CDR must operate on each CO₂ molecule, there are no easy wins at the scale of the climate problem. Although atmospheric CDR approaches might be able to cost-effectively address some portion of our CO₂ emissions, it cannot be assumed that these approaches will be able to feasibly be scaled up to address a major fraction of current CO₂ emissions. As discussed in Chapter 5 of the companion volume (*Climate Intervention: Reflecting Sunlight to Cool Earth*), the committee recommends that efforts to address climate change should continue to focus most heavily on mitigating greenhouse gas emissions in combination with adapting to the impacts of climate change because these approaches do not present poorly defined and quantified risk and are at a greater state of technological readiness.

VALUE

Some CDR approaches, such as afforestation and reforestation, are already recognized as valuable both for the CDR and sequestration, but also for other co-benefits, including ecosystem services such as protection of watersheds from erosion, nutrient retention, good water quality, wildlife habitat and diversity, recreational opportunities, and other social benefits (Millennium Ecosystem Assessment, 2010; Plantinga and Wu, 2003). Accelerated mineral-weathering approaches aim to accelerate the natural processes that neutralize CO₂ acidity (Kheshgi, 1995) and thus could potentially provide substantial environmental benefit to neutralizing some of the acidification of the ocean caused by excess anthropogenic CO₂. There may be other CDR approaches that may be unable to scale up to match current or future CO₂ emissions, but they may nevertheless be cost effective at modest scale and/or provide valuable co-benefits.

Costs for various CO₂ capture approaches currently range from \$50 to more than \$1,000 per ton CO₂ (tCO₂), and costs for various sequestration approaches range from \$6/tCO₂ to hundreds of dollars per ton of CO₂ (see Table 2.2). As such, some CDR approaches might not be cost competitive with least-cost mitigation options today but could potentially become cost competitive at some future date if and when costs of deployment decline and a price has been placed on carbon emissions that reflects the social costs of those emissions. The most recent estimate for the social cost of a ton of carbon emissions to society is \$12 to \$120 (Interagency Working Group on Social Cost of Carbon, 2013; see also <http://www.epa.gov/climatechange/EPAactivities/economics/scc.html>).

RESEARCH

Developing the ability to capture climatically important amounts of CO₂ from the atmosphere and sequester it reliably and safely on scales of significance to climate change requires research into how to make the more promising options more effective, more environmentally friendly, and less costly. At this early stage successful development also requires soliciting and encouraging new synergies and approaches to CDR. Such research investments would accelerate this development and could help avoid some of the greatest climate risks that the lack of timely emissions reduction may make inevitable. The committee recognizes that a research program in CDR faces difficult challenges to create viable, scalable, and affordable techniques, but the committee argues that the situation with human-induced climate change is critical enough (see Chapter 1) that these CDR techniques need to be explored to assess their potential viability, and potential breakthrough technologies need to be nurtured as they arise.

Prioritizing a research portfolio will be challenging, as will the temptation to narrow the portfolio to those technologies closer to economic feasibility. Ongoing relevant research (e.g., bioenergy, CCS) also has the potential of advancing atmospheric CDR technologies and approaches. The scope of existing relevant programs could be broadened to include a wider portfolio. No major new bureaucracies are needed to facilitate enhanced research in this area.

It is possible that future research and development efforts could provide low-cost ways to reduce net anthropogenic CO₂ emissions through CO₂ capture from the atmosphere. However, the sheer mass of CO₂ under consideration, and its diffuse presence in the atmosphere, present challenges to any effort to remove a substantial fraction of it and dispose of it safely in a reliable reservoir.

Overall, the committee concludes that there would be great value in the United States pursuing

- An expanded program of research and field studies to assess and improve strategies for performing and monitoring geologic sequestration;
- The exploration of strategies such as accelerated mineral weathering that enhance ocean uptake of carbon dioxide and/or increase the ocean's ability to store carbon without causing adverse effects (ocean iron fertilization does not appear to be a promising strategy in this regard);
- Continued research on combining biomass energy with carbon dioxide capture and sequestration, including exploration of approaches that do not form and sequester concentrated CO₂; and

- A program of fundamental research in science and technology to solicit, foster, and develop approaches for scrubbing carbon dioxide from the atmosphere that hold the potential to bring costs and energetics into a potentially feasible range.

CDR approaches that have value on a smaller scale can have other co-benefits but are unlikely to individually scale to contribute significantly to the problem at hand. The committee concludes there would be value in pursuing

- Research on land use management techniques that promote carbon sequestration and
- Research on accelerated weathering as a CO₂ removal or sequestration approach that would allow conversion to stable, storable, or useful carbonates and bicarbonates.

Note that these research topics are not prioritized and, although they are listed together, these research topics do not necessarily require equal levels of investment.

The development of a research program on CDR may involve modeling, field research, satellite measurements, and laboratory studies. As such, this research will likely involve the efforts of multiple agencies, laboratories, and universities. It would be useful to have some coordination of the research efforts involved in these multiple organizations to avoid duplication and ensure that the most important questions are addressed. Although other organizations could perhaps fill this coordinating role, the U.S. Global Change Research Program (USGCRP) is the most obvious possibility and is a logical choice given the overlap of many research topics with the climate change research agenda. USGCRP coordinates and integrates federal research on changes in the global environment and their implications for society (<http://www.globalchange.gov/about/overview>). Thirteen departments and agencies participate in USGCRP, and USGCRP agencies interact with a wide variety of groups around the world including international, national, state, tribal, and local governments, businesses, professional and other nonprofit organizations, the scientific community, and the public.

Recommendation 2:⁶ The committee recommends research and development investment to improve methods of carbon dioxide removal and disposal at scales that

⁶ Note that Recommendations 1, 3, 4, and 5 involve both CDR and albedo modification or albedo modification only, and are found in the Summary of this report and discussed in more detail in Chapter 5 of the companion report, *Climate Intervention: Reflecting Sunlight to Cool Earth*.

matter, in particular to minimize energy and materials consumption, identify and quantify risks, lower costs, and develop reliable sequestration and monitoring.

- It is increasingly likely that, as a society, we will need to deploy some forms of CDR to avoid the worst impacts of climate change, but without research investment now such attempts at climate mitigation are likely to fall well short of needed targets.
- Many of the strategies discussed for carbon dioxide removal provide viable and reasonably low-risk approaches to reducing atmospheric concentrations of carbon dioxide. Because the natural rate of carbon dioxide removal is currently being overwhelmed by anthropogenic emissions, additional CDR would need to be sustained at large scales over very long periods of time to have a significant effect on carbon dioxide concentrations and the associated risks of climate change.
- Absent some unforeseen technological innovation, large-scale carbon dioxide removal techniques have costs comparable to or exceeding those of avoiding carbon dioxide emissions by replacing fossil fuels with low-carbon-emission energy sources. Widespread CDR will likely occur only in a policy environment in which there are limits or a price is imposed on emissions of carbon dioxide, and in that case CDR will compete directly with mitigation on a cost basis (i.e., cost per ton of CO₂ removed versus cost per ton of CO₂ emission avoided).
- Decisions regarding deployment of CDR will be largely based on cost and scalability. Carbon dioxide removal strategies might entail some local or even regional environmental risk, but in some cases, CDR strategies may have also substantial co-benefits.
- Several federal agencies should have a role in defining and supporting CDR research and development. The committee recommends a coordinated approach that draws upon the historical strength of the various agencies involved and uses existing coordination mechanisms, such as the U.S. Global Change Research Program, to the extent possible.

CARBON DIOXIDE REMOVAL AND CONTROVERSY

For decades, the UN Framework Convention on Climate Change has recognized the important role of forests in CO₂ removal from the atmosphere with reliable sequestration, although there has been controversy over how best to measure and assign credit for captured CO₂. Far more controversial has been the suggestion that CO₂ could be removed from the atmosphere by fertilizing the ocean with iron, for which there is a near consensus that at climatically relevant levels of deployment potential risks

outweigh potential benefits. Indeed, few observers today think that iron fertilization of the ocean is an attractive and effective way to markedly reduce atmospheric CO₂ concentrations.

Ocean alkalization and/or ocean iron fertilization would need to be applied over vast regions to have a chance at making a climatically detectable difference, and thus both ideas potentially involve intervening in Earth system processes, for better or worse, at a massive scale. The idea of interfering in Earth system properties at large scale is also common to albedo modification proposals, such as putting particles in the stratosphere. Furthermore, both involve activities that have effects across international borders and/or on an international commons such as the ocean. These properties have caused some (e.g., The Royal Society, 2009) to lump CDR and albedo modification (“solar geoengineering” or “solar radiation management”) together under a single umbrella term (“geoengineering”).

In some contexts, it might be useful to treat various CDR proposals and albedo modification proposals jointly. This is especially true of those CDR approaches that raise novel risks and governance issues (e.g., ocean fertilization, ocean alkalization [or “ocean alkalinity addition”]). However, many proposed CDR approaches do not pose novel risks or governance issues (e.g., land management, BECCS).

For the next decades and perhaps the remainder of the century, atmospheric CO₂ emissions are likely to be much greater than the amount of atmospheric CO₂ removed. Thus, from a practical standpoint, it is often useful to consider these proposals in the context of other proposed means of reducing net CO₂ emissions (e.g., near-zero-emission energy sources and increased energy efficiency).

CONCLUDING THOUGHTS

Addressing the challenge of climate change will require a portfolio of solutions, and as the anthropogenic contributions to climate change persist, the effectiveness of that portfolio becomes increasingly critical. Both CDR strategies and other technologies and approaches that lead to lower CO₂ concentrations in the atmosphere (e.g., CCS, solar energy, wind energy, and energy efficiency improvements) offer the potential to slow the growing concentrations of CO₂ and other GHGs in the atmosphere. Although CDR techniques hold promise, they are not sufficiently advanced to the point of being deployable at scales and costs necessary to substantively address the challenges climate change represents, nor are they likely to ever be sufficient to singularly address these challenges. To determine if and when these techniques can be a major component of a mitigation portfolio requires research targeted at assessing and improving

the efficacy of these techniques for reducing atmospheric carbon content as well as fostering new methods and approaches. Key areas of focus are provided in the previous section, “Research.”

It is clear, however, that atmospheric CO₂ removal is and can be valuable, especially given the current likelihood that total carbon emissions will exceed the threshold experts believe will produce irreversible environmental effects. For example, land management and reforestation can remove CO₂ from the atmosphere and, when done well, can have substantial co-benefits. BECCS could represent an important mechanism for reducing atmospheric CO₂ concentrations in the future once fossil fuel emissions are significantly reduced. Other approaches have been proposed (e.g., DACS and accelerated chemical weathering) that would benefit from additional research and analysis. Some of these approaches may never be cost effective, creating challenges to the development of a research portfolio that does not negatively affect research into mitigation opportunities that may be less expensive. Overall, there is much to be gained in pursuing multiple parts of a portfolio of climate change strategies including research on various CDR techniques.

To be effective, carbon dioxide removal must be pursued collectively by a number of international participants. In contrast, albedo modification could be undertaken unilaterally. The environmental and climate system consequences of albedo modification are as yet poorly characterized, and the governance issues are complex as well. Some forms of carbon dioxide removal also involve environmental risk, for example from changes in ocean ecology or induced seismicity from underground injection of CO₂ or from the use of inappropriate reservoirs. The barriers to deployment of CDR approaches are largely related to high costs, slow implementation, limited capacity, and policy considerations. If carbon removal technologies are to be viable, it is critical now to embark on a research program to lower the technical barriers to efficacy and affordability while remaining open to new ideas, approaches, and synergies. As is true for mitigation and adaptation, society must take advantage as soon as possible of CDR strategies that can help avoid the worst effects of warming. We will lose the opportunity if society delays in research and development to lower the technical barriers to efficacy and affordability of CDR for deployment.

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Statement of Task for the Committee

The Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts was charged with the following task:

An ad hoc committee will conduct a technical evaluation of a limited number of proposed geoengineering techniques, including examples of both solar radiation management and carbon dioxide removal techniques, and comment generally on the potential impacts of deploying these technologies, including possible environmental, economic, and national security concerns. The study will

1. Evaluate what is currently known about the science of several (3 or 4) selected example techniques, including potential risks and consequences (both intended and unintended), such as impacts, or lack thereof, on ocean acidification;
2. Describe what is known about the viability for implementation of the proposed techniques including technological and cost considerations;
3. Briefly explain other geoengineering technologies that have been proposed (beyond the selected examples); and
4. Identify future research needed to provide a credible scientific underpinning for future discussions.

The study will also discuss historical examples of related technologies (e.g., cloud seeding and other weather modification) for lessons that might be learned about societal reactions, examine what international agreements exist that may be relevant to the experimental testing or deployment of geoengineering technologies, and briefly explore potential societal and ethical considerations related to geoengineering. This study is intended to provide a careful, clear scientific foundation that informs ethical, legal, and political discussions surrounding geoengineering.

This study was sponsored by the U.S. intelligence community, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Department of Energy, and the National Academies.

Committee Biographies

Dr. Marcia K. McNutt, American Association for the Advancement of Science (*Committee Chair*) is the former Director of the U.S. Geological Survey and current Editor-in-Chief of the *Science* family of journals. She is a member of the National Academy of Sciences, the American Philosophical Society, and the American Academy of Arts and Sciences. She was awarded by the American Geophysical Union the Macelwane Medal in 1988 for research accomplishments by a young scientist and the Maurice Ewing Medal in 2007 for her significant contributions to deep-sea exploration. She holds honorary doctoral degrees from the University of Minnesota, Colorado College, Monmouth University, and Colorado School of Mines. Dr. McNutt received her Ph.D. in earth sciences from Scripps Institution of Oceanography.

Dr. Waleed Abdalati, is Director of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, a professor in the Department of Geography, and Director of the Earth Science and Observation Center. In 2011 and 2012 he was on a leave of absence from the university to serve as the Chief Scientist at the National Aeronautics and Space Administration (NASA). In this role he oversaw the full portfolio of NASA science activities and served as advisor on agency science matters to the NASA administrator and NASA leadership. His research has focused on the study of polar ice cover using satellite and airborne instruments. During his initial tenure at NASA from 1998 to 2008 he held a variety of positions in the areas of scientific research, program management, scientific management, and mission science oversight. Prior to his joining NASA, he worked as an engineer in the aerospace industry. Dr. Abdalati received a B.S. in mechanical engineering from Syracuse University in 1986, and an M.S. in aerospace engineering and a Ph.D. in geography from the University of Colorado in 1991 and 1996, respectively.

Dr. Ken Caldeira is a senior member of the Carnegie Institution's Department of Global Ecology staff and a professor, by courtesy, in Stanford's Environmental Earth System Sciences department. Dr. Caldeira has a wide-spectrum approach to analyzing the world's climate systems. He studies the global carbon cycle; marine biogeochemistry and chemical oceanography, including ocean acidification and the atmosphere-ocean carbon cycle; land cover and climate change; the long-term evolution of climate and geochemical cycles; and energy technology. In 2001, he was a contributing author to the Intergovernmental Panel on Climate Change (IPCC) Working Group I Third Assessment Report. In 2005, he was coordinating lead author for the ocean storage

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chapter of the IPCC Special Report on Carbon Capture and Storage. He was on the U.K. Royal Society ocean acidification panel in 2005 and geoengineering panel in 2009. He was a lead author of the 2007 U.S. *State of the Carbon Cycle* report. He was a co-author of the 2010 National Academy of Sciences (NAS) *America's Climate Choices* report. In 2010, Caldeira was elected Fellow of the American Geophysical Union. Caldeira was a contributing author to the 2014 IPCC Fifth Assessment Report (IPCC AR5).

Dr. Scott Doney is a Senior Scientist and Chair of the Department of Marine Chemistry and Geochemistry at the Woods Hole Oceanographic Institution (WHOI). He graduated with a B.A. in chemistry from the University of California, San Diego, in 1986 and a Ph.D. in chemical oceanography from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography in 1991. He was a postdoctoral fellow and later a scientist at the National Center for Atmospheric Research, before returning to Woods Hole in 2002. He was awarded the James B. Macelwane Medal from the American Geophysical Union (AGU) in 2000, an Aldo Leopold Leadership Fellow in 2004, the WHOI W. Van Alan Clark Sr. Chair in 2007, and the A.G. Huntsman Award for Excellence in Marine Science in 2013. He is an AGU Fellow (2000) and an American Association for the Advancement of Science (AAAS) Fellow (2010). His science interests span oceanography, climate, and biogeochemistry. Much of his research focuses on how the global carbon cycle and ocean ecology respond to natural and human-driven climate change. A key focus is on ocean acidification due to the invasion into the ocean of carbon dioxide from fossil fuel burning. He was the inaugural chair of the U.S. Ocean Carbon and Biogeochemistry Program, past director of the WHOI Ocean and Climate Change Institute, and a convening lead author of the Oceans and Marine Resources chapter of the 2014 U.S. National Climate Assessment.

Dr. Paul G. Falkowski is Bennett L. Smith Professor of Business and Natural Resources at Rutgers, The State University of New Jersey, and Director of the Rutgers Energy Institute. His research interests include biogeochemical cycles, photosynthesis, biological oceanography, molecular biology, biochemistry and biophysics, physiological adaptation, plant physiology, evolution, mathematical modeling, and symbiosis. Dr. Falkowski is also the Lead Principal Investigator in the Environmental Biophysics and Molecular Ecology (EBME) program. That program focuses on molecular biology and biophysics to address key questions in biological oceanography and marine biology. The EBME program provides a laboratory in the Institute of Marine and Coastal Sciences at Rutgers University that addresses the application of similar techniques to primary production, nitrogen fixation, and other rate-determining processes in aquatic as well as terrestrial ecosystems. Dr. Falkowski has received many awards; his most recent include the Board of Trustees Award for Excellence in Research, Rutgers University

(2000); Vernadsky Medal, European Geosciences Union (2005); and Board of Governors Professor, Rutgers University (2005). Dr. Falkowski was elected to the NAS as a member in 2007. He has also received numerous grants, some from NASA, the National Science Foundation (NSF), the Department of Defense, the Department of Energy (DOE), and the Moore Foundation. Dr. Falkowski received his Ph.D. in biology at the University of British Columbia.

Dr. Steve Fetter is Associate Provost for Academic Affairs at the University of Maryland. He has been a professor in the Maryland School of Public Policy since 1988, serving as Dean from 2005 to 2009. In 2009–2012 he was Assistant Director At-Large in the Office of Science and Technology Policy in the White House. Dr. Fetter is a member of the Council on Foreign Relations, a Fellow of the American Physical Society (APS), and a recipient of the APS Joseph A. Burton Forum Award. He has been a member of the Director of National Intelligence’s Intelligence Science Board and the Department of Energy’s Nuclear Energy Advisory Committee, served as President of the Association of Professional Schools of International Affairs and Vice Chairman of the Federation of American Scientists (FAS), and received the FAS Hans Bethe Science in the Public Service award. He has been an advisor to the U.S. departments of State, Defense, and Energy and has held visiting positions at Stanford, Harvard, and MIT. He received a Ph.D. in energy and resources from the University of California, Berkeley, and an S.B. in physics from MIT.

Dr. James R. Fleming is a historian of science and technology and Professor of Science, Technology and Society at Colby College. He is a fellow of the AAAS and the American Meteorological Society (AMS), series editor of *Palgrave Studies in the History of Science and Technology*, contributing author to the Intergovernmental Panel on Climate Change, and chair of the AAAS Section on Societal Impacts of Science and Engineering. Dr. Fleming earned a B.S. in astronomy from Pennsylvania State University, an M.S. in atmospheric science from Colorado State University, and an M.A. and Ph.D. in history from Princeton University. He has held a number of major fellowships and lectureships, including the Charles A. Lindbergh Chair in Aerospace History at the Smithsonian Institution, the Roger Revelle Fellowship of the AAAS, the Ritter Memorial Fellowship at the Scripps Institution of Oceanography, the H. Burr Steinbach Lectureship at the Woods Hole Oceanographic Institute, the Gordon Cain Conference Fellowship at the Chemical Heritage Foundation, a Woodrow Wilson Center policy scholarship, and a Scholar’s Award from the U.S. National Science Foundation. He is currently a visiting scholar in the history department at Columbia University.

Dr. Steven P. Hamburg is Chief Scientist at Environmental Defense Fund. He is an ecosystem ecologist specializing in the impacts of disturbance on forest structure

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and function. He has served as an advisor to both corporations and nongovernmental organizations on ecological and climate change mitigation issues. Previously, he spent 16 years as a tenured member of the Brown University faculty and was founding Director of the Global Environment Program at the Watson Institute for International Studies. Dr. Hamburg is the Co-Chair of the Royal Society's Solar Radiation Management Governance Initiative and a member of the U.S. Department of Agriculture Advisory Committee on Research, Economics, Extension and Education. He has been the recipient of several awards, including recognition by the Intergovernmental Panel on Climate Change as contributing to its award of the 2007 Nobel Peace Prize. Dr. Hamburg earned a Ph.D. in forest ecology from Yale University.

Dr. M. Granger Morgan is Lord Chair Professor in Engineering; Professor and Department Head, Engineering and Public Policy; Professor in Electrical and Computer Engineering; and professor in The H. John Heinz III School of Public Policy and Management, Carnegie Mellon University (CMU). Dr. Morgan's research interests are focused on policy problems in which technical and scientific issues play a central role. Methodological interests include problems in the integrated analysis of large complex systems; problems in the characterization and treatment of uncertainty; problems in the improvement of regulation; and selected issues in risk analysis and risk communication. Application areas of current interest include global climate change; the future of the energy system, especially electric power; risk analysis, including risk ranking; health and environmental impacts of energy systems; security aspects of engineered civil systems; national research and development policy; radio interference on commercial airliners; issues of privacy and anonymity; and a number of general policy, management, and manpower problems involving science and technology. Most of Dr. Morgan's professional career has been spent at CMU with short stints at Brookhaven National Labs, the National Science Foundation, and the University of California, San Diego. His professional activities include a large number of publications, memberships on numerous panels, including the Electric Power Research Institute Advisory Board (which he previously chaired) and the Scientific and Technical Council of the International Risk Governance Council (which he chairs). He is past chair of the Environmental Protection Agency (EPA) Science Advisory Board. He is a member of the NAS and has served on and chaired many National Research Council (NRC) committees. He earned his Ph.D. in applied physics and information science from the University of California, San Diego.

Dr. Joyce E. Penner is the Ralph J. Cicerone Distinguished University Professor of Atmospheric Science and Associate Chair for the Atmospheric, Oceanic, and Space Sciences Department. Dr. Penner's research focuses on improving climate models through the addition of interactive chemistry and the description of aerosols and their direct and indirect effects on the radiation balance in climate models. She is interested

in cloud and aerosol interactions and cloud microphysics, climate and climate change, and model development and interpretation. Dr. Penner has been a member of numerous advisory committees related to atmospheric chemistry, global change, and Earth science, including the IPCC, which was awarded the 2007 Nobel Peace Prize. She was the coordinating lead author for IPCC (2001), Chapter 5, on aerosols and report coordinator for the 1999 IPCC report: *Aviation and the Global Atmosphere*. Dr. Penner received a B.A. in applied mathematics from the University of California, Santa Barbara, and her M.S. and Ph.D. in applied mathematics from Harvard University. She is currently a member of the NRC U.S. National Committee for the International Union of Geodesy and Geophysics, as well as the Vice-Chair of the Committee on Earth Science and Applications from Space. Prior NRC service includes being a member of the Space Studies Board, the planning committee for the Workshop on Uncertainty Management in Remote Sensing of Climate Data, and the Panel on Climate Variability and Change for the 2007 decadal survey on Earth science and applications from space.

Dr. Raymond T. Pierrehumbert is the Louis Block Professor in Geophysical Sciences at the University of Chicago, having earlier served on the atmospheric science faculties of Massachusetts Institute of Technology (MIT) and Princeton. His research work has dealt with a wide range of problems in the physics of climate, including anthropogenic climate change, climate of the early Earth, climate of Mars and Titan, and most recently exoplanet climate. He was a lead author of the IPCC Third Assessment Report, and a co-author of the NRC report on abrupt climate change and of the report on climate stabilization targets. He is a Fellow of the AGU, and in recognition of his work on climate he has been named Chevalier de l'Ordre des Palmes Academiques by the Republic of France. Dr. Pierrehumbert is the author of *Principles of Planetary Climate*, a textbook on comparative planetary climate published by Cambridge University Press, and, with David Archer, co-author of *The Warming Papers* (Wiley/Blackwell). He received his Ph.D. from MIT.

Dr. Philip J. Rasch serves as the Chief Scientist for Climate Science at the Pacific Northwest National Laboratory (PNNL), a Department of Energy Office of Science research laboratory. In his advisory role, he provides leadership and direction to PNNL's Atmospheric Sciences and Global Change Division. The division conducts research on the long-term impact of human activities on climate and natural resources using a research strategy that starts with measurements and carries that information into models, with a goal of improving the nation's ability to predict climate change. Dr. Rasch provides oversight to more than 90 researchers who lead and contribute to programs within a number of government agencies and industry. These programs focus on climate; aerosol and cloud physics; global and regional scale modeling; integrated assessment of global change; and complex regional meteorology and chemistry.

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Dr. Rasch earned bachelor's degrees in chemistry and atmospheric science from the University of Washington and master's and Ph.D. degrees in meteorology from Florida State University.

Dr. Lynn M. Russell is professor in the Climate, Ocean, and Atmosphere program at Scripps Institution of Oceanography on the faculty of the University of California, San Diego, where she has led the Climate Sciences Curricular Group since 2009. Her research is in the area of aerosol particle composition and microphysics, including the behavior of particles from both biogenic and combustion processes. Her research group pursues both modeling and measurement studies of atmospheric aerosols, using the combination of these approaches to advance our understanding of fundamental processes that affect atmospheric aerosols. She completed her undergraduate work at Stanford University, and she received her Ph.D. in chemical engineering from the California Institute of Technology for her studies of marine aerosols. Her postdoctoral work as part of the National Center for Atmospheric Research Advanced Studies Program investigated aerosol and trace gas flux and entrainment in the marine boundary layer. She served on the faculty of Princeton University in the Department of Chemical Engineering before accepting her current position at Scripps in 2003. She has been honored with young investigator awards from the Office of Naval Research, NASA, the Dreyfus Foundation, NSF, and the James S. McDonnell Foundation. In 2003 she received the Kenneth T. Whitby Award from the American Association for Aerosol Research (AAAR; 2003) for her contributions on atmospheric aerosol processes, and she was named AAAR Fellow in 2013.

Dr. John T. Snow, is a Regents' Professor of Meteorology and Dean Emeritus of the College of Atmospheric and Geographic Sciences at the University of Oklahoma. Currently, Dr. Snow's professional interests lie in the field of "Earth system science," merging research in the Earth and life sciences to generate a comprehensive explanation for "how the world works." In recent years, Dr. Snow has been involved in a number of local and regional economic development projects and technology transfer efforts. Dr. Snow is involved with a number of professional organizations, serving as an AMS Fellow, a Royal Meteorological Society Fellow, and a member of the NSF Geosciences Advisory Committee, to name a few. The AMS has honored Dr. Snow with the Charles Anderson Award for his efforts in improving education and diversity in the atmospheric sciences, and the Cleveland Abbey Award for his excellent service to both the Society and the profession. Dr. Snow earned both his B.S. and M.S. in electric engineering from the Rose-Hulman Institute of Technology, and his Ph.D. in atmospheric sciences from Purdue University in 1977.

RADM David W. Titley, USN [Ret.], is currently the Director of the Center for Solutions to Weather and Climate Risk at Pennsylvania State University. He is a nationally known expert in the field of climate, the Arctic, and national security. He served as a naval officer for 32 years and rose to the rank of Rear Admiral. Dr. Titley's career included duties as Oceanographer and Navigator of the Navy and Deputy Assistant Chief of Naval Operations for Information Dominance. While serving in the Pentagon, Dr. Titley initiated and led the U.S. Navy's Task Force on Climate Change. After retiring from the Navy, Dr. Titley served as the Deputy Undersecretary of Commerce for Operations, the Chief Operating Officer position at the National Oceanic and Atmospheric Administration. Dr. Titley has spoken across the country and throughout the world on the importance of climate change as it relates to national security. He was invited to present on behalf of the Department of Defense at both congressional hearings and the IPCC meetings from 2009 to 2011. He has presented a TEDx talk on climate change and speaks regularly on this topic at universities across the country. He currently serves on the Advisory Board of the Center of Climate and Security based in Washington, DC. Dr. Titley holds a B.S. in meteorology from the Pennsylvania State University. From the Naval Postgraduate School, he earned an M.S. in meteorology and physical oceanography, and a Ph.D. in meteorology. He was elected a Fellow of the American Meteorological Society in 2009 and was awarded an honorary doctorate from the University of Alaska, Fairbanks.

Dr. Jennifer Wilcox is an Assistant Professor of Energy Resources Engineering in the School of Earth Sciences and an affiliate faculty member in the Emmet Interdisciplinary Program for the Environment and Resources at Stanford University. Her research efforts include sorbent design and testing for carbon and trace-metal capture from fossil fuels, adsorption studies of CO₂ on coal and gas shales, and membrane design for N₂ and H₂ separations. She also heads the Clean Conversion Laboratory in the School of Earth Sciences. She received the NSF Career Award (2005) and the Army Research Office Young Investigator Award (2009). Wilcox earned a B.A. in mathematics from Wellesley College, and an M.A. in physical chemistry and a Ph.D. in chemical engineering from the University of Arizona. She recently authored the first textbook on carbon capture.

Acronyms and Abbreviations

APS	American Physical Society
BECCS	bioenergy with carbon capture and sequestration
BLM	Bureau of Land Management
CCS	carbon capture and sequestration
CDR	carbon dioxide removal
CKD	cement kiln dust
DAC	direct air capture
DACS	direct air capture and sequestration
EOR	enhanced oil recovery
FAO	Food and Agriculture Organization
GCAM	Global Change Assessment Model
GHG	greenhouse gas
IAM	integrated assessment model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	life-cycle analysis
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
OFE	Office of Fossil Energy
OIF	ocean iron fertilization
ReMIND	Regional Model of Investments and Development
RCP	representative concentration pathway
SRES	Special Report on Emissions Scenarios

APPENDIX C

SRM	solar radiation management
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey