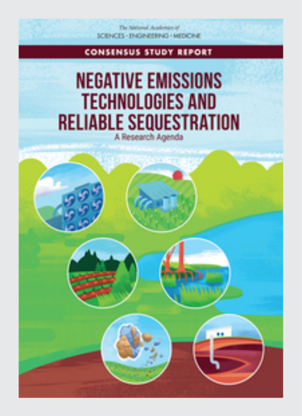

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NEGATIVE EMISSIONS TECHNOLOGIES AND RELIABLE SEQUESTRATION

A Research Agenda

Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration

Board on Atmospheric Sciences and Climate

Board on Energy and Environmental Systems

Board on Agriculture and Natural Resources

Board on Earth Sciences and Resources

Board on Chemical Sciences and Technology

Ocean Studies Board

Division on Earth and Life Studies

A Consensus Study Report of

The National Academies of
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this report nor did they see the final draft before its release. The review of this report was overseen by **Warren M. Washington,** National Center for Atmospheric Research Climate and Global Dynamics Division, and **Antonio J. Busalacchi,** University Corporation for Atmospheric Research. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring Committee and the National Academies.

Preface

Humans started adding fossil CO_2 to the atmosphere about 300 years ago and accelerated land use emissions by expanding croplands and pastures. The unintended consequence of these activities is a 120 ppm increase in atmospheric concentration of CO_2, which is now changing our climate. In response, international action is being taken to reduce net greenhouse gas emissions and limit global warming below 2°C. Most climate mitigation technologies are intended to decrease the rate at which we take additional carbon from fossil fuel reservoirs and ecosystems and add it to the atmosphere as CO_2. These include renewable electricity, increased energy efficiency, and carbon capture and storage of emissions from fossil power plants. This report focuses on the reverse: technologies that take CO_2 out of the atmosphere and put it back into geologic reservoirs and terrestrial ecosystems. These negative emissions technologies, or NETs, have received much less attention by researchers than traditional mitigation technologies.

The Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration was created to recommend a detailed research and development plan for NETs that: (1) use biological processes to increase carbon stocks in soils, forests, and wetlands, (2) produce energy from biomass, while capturing and storing the resulting CO_2 emissions, (3) use chemical processes to capture CO_2 directly from the air and then sequester it in geologic reservoirs, and (4) enhance geologic processes that capture CO_2 from the atmosphere and permanently bind it with rocks. These NETs are at vastly different stages of readiness. Some are close to being ready for large-scale deployment, while others require basic scientific research. The committee met six times from May 2017 to February 2018 and, associated with four of these meetings, held open public webinars and workshops that gathered extensive input from scientists across academia, federal and state agencies, industry, and nongovernmental organizations. This input is summarized in five separate publicly available workshop proceedings that document the committee's information gathering activities and to help inform the public about NETs.

On a final, more personal note, I would like to thank the committee members, who gave so freely of their time and talent, and who were models of interdisciplinary listening and respect. Thanks to the staff of the National Academies of Sciences, Engineering, and Medicine (NASEM), who organized us, improved our writing, and helped us crystalize our thoughts. They worked tirelessly through our workshops and closed sessions, innumerable calls, and many drafts. And thanks to those who presented their research to the committee; your selfless service enriched this report. Finally, thanks to the reviewers who helped to sharpen and focus the report.

Stephen Pacala, Chair
Committee on Developing a Research Agenda for
Carbon Dioxide Removal and Reliable Sequestration

Contents

Summary

As understanding of the risks and damages of climate change has improved, almost all nations have committed to limit total global warming to less than 2°C over preindustrial levels, with an aspirational target of 1.5°C. Meeting a 2°C target is becoming exceedingly challenging; the global mean temperature has already risen about 1°C over the 20th century. Most climate and integrated assessment models project that the concentration of atmospheric carbon dioxide (CO_2) would have to stop increasing (and perhaps start decreasing) by the second half of the century for there to be a reasonable chance of limiting warming and the associated dangerous climate impacts.

Fossil fuel consumption, agriculture, land-use change, and cement production are the dominant anthropogenic sources of CO_2 to the atmosphere. The focus of climate mitigation is to reduce energy sector emissions by 80-100 percent, requiring massive deployment of low-carbon technologies between now and 2050. Progress toward these targets could be made by deploying negative emissions technologies (NETs), which remove carbon from the atmosphere and sequester it. Under the present conditions, where fossil CO_2 is continuously added to the atmosphere, removing CO_2 from the atmosphere and storing it has exactly the same impact on the atmosphere and climate as simultaneously preventing emission of an equal amount of CO_2. NETs have been part of the portfolio to achieve net emissions reductions, at least since reforestation, afforestation, and soil sequestration were brought into the United Nations Framework Convention on Climate Change, albeit as mitigation options, more than two decades ago. Recent analyses found that deploying NETs may be less expensive and less disruptive than reducing some emissions, such as a substantial portion of agricultural and land-use emissions and some transportation emissions.

In 2015, the National Academies published *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*, which described and initially assessed NETs and sequestration technologies. This report acknowledged the relative paucity of research on NETs and recommended development of a research agenda that covers all aspects of NETs from fundamental science to full-scale deployment. To address this need, the National Academies convened the Committee on Developing a Research Agenda for Carbon Dioxide Removal and Sequestration to assess the benefits, risks, and "sustainable scale potential" for NETs and sequestration and to define the essential components of a research and development program, including its estimated costs and potential impact (Box S.1). The full Statement of Task is presented in Box 1.4. The

BOX S.1
ASSESSING THE NEED FOR NEGATIVE EMISSIONS TECHNOLOGIES

To complete its task, the committee assessed the urgency of developing new and/or improved NETs. Apart from two NETs with large co-benefits, NETs will only be deployed to reduce atmospheric CO_2. Thus, the coming economic and social demand for NETs can only be assessed in reference to a plan for climate mitigation. Therefore, the committee based its assessment on the target from the Paris agreement that limits warming to less than 2°C and ideally 1.5°C. And recently, the Intergovernmental Panel on Climate Change (IPCC) concluded that limiting global warming to 1.5°C with limited or no overshoot will require the use of NETs by the middle of this century.

This report's statements about the *need* for an emissions reduction of a particular amount should not be interpreted as normative statements (a value judgment on what should be), but rather as statements about the action required *given a decision to meet the Paris agreement or to provide NETs to the international market created by such a decision by most nations, many corporations, and several U.S. states and local governments*. Nonetheless, the committee is acutely aware that the U.S. government has announced an intention to withdraw from the Paris agreement.

It is useful to ask how the report's conclusions would differ without the constraint of the Paris agreement. The committee believes that its conclusions and recommendations are generally robust, simply because the economic rewards for success would be so large. This is due to the ongoing commitment by the U.S. government to reduce the contributors to climate change, as evidenced by the recently adopted 45Q rule[a] that provides a \$50/t CO_2 tax credit for capture and storage,[b] and the ongoing commitment to the Paris agreement by states, local governments, corporations, and other countries.

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[a] https://www.law.cornell.edu/uscode/text/26/45Q.

[b] Although the term "storage" might imply accumulation for future use, the committee uses this term interchangeably with the term "sequestration" in accordance with the literature reviewed.

committee held a series of public workshops and meetings to inform its deliberations and the writing of this report.

MITIGATION IN A NET ZERO EMISSIONS SYSTEM

Studies using integrated assessment models that link greenhouse gas emissions, the economy, and climate conclude that the reductions in net anthropogenic emissions required to meet even the 2°C target will be difficult and expensive to achieve, even with foreseeable technological breakthroughs. In its Fifth Assessment Report (2014), the Intergovernmental Panel on Climate Change (IPCC) projects high costs for reducing the concentration of atmospheric CO_2, with costs in many scenarios reaching more than \$1,000 per ton of CO_2 emissions by 2100. Stopping the growth of atmospheric CO_2 requires that anthropogenic emissions are less than or equal to natural and anthropogenic carbon sinks—not that they cease altogether. As reported in IPCC (2014b), the lowest cost trajectories for achieving the 2°C target typically include massive deployment of one specific type of NET, bioenergy with carbon capture and sequestration (BECCS), to avoid the even steeper costs associated with relying on emissions cuts alone. However, BECCS at this scale requires more feedstock than is available from biomass waste. For example, 30 million to 43 million hectares is required to raise BECCS feedstocks per Gt/y CO_2 of negative emissions. Thus, 10 Gt/y CO_2 of negative emissions from BECCS requires hundreds of millions of hectares of land, which is almost 40 percent of global cropland according to some studies reviewed in IPCC (2014b).

The committee repeatedly encountered the view that NETs will primarily be deployed to reduce atmospheric CO_2 after fossil emissions are reduced to near zero. In contrast, because it will likely be very expensive to decrease anthropogenic emissions once they reach low levels, methods for reduced and negative emissions will probably be competitors for an extended period, even during a sustained period of net negative global emissions (see Figure S.1). For example, few alternatives to chemical fuels are likely to exist for commercial aviation. One option for zero net aviation emissions

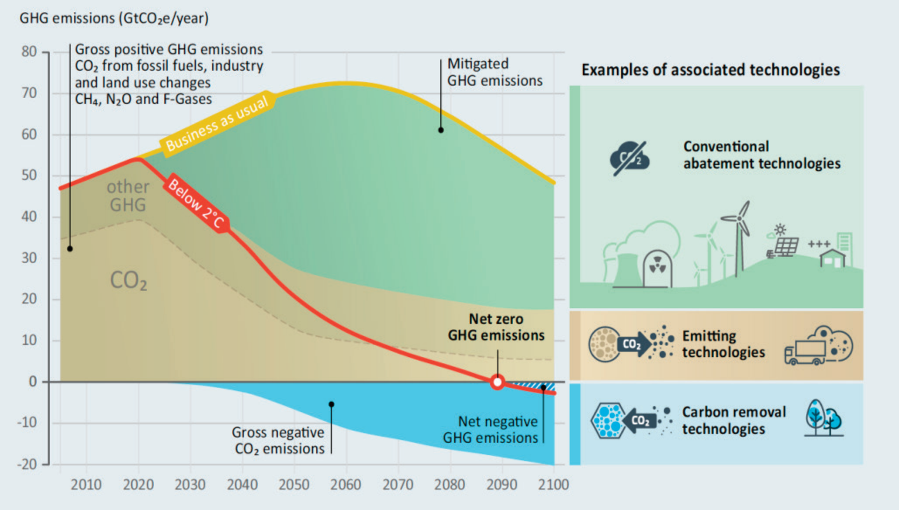

FIGURE S.1. Scenario of the role of negative emissions technologies in reaching net zero emissions.
NOTE: For any concentration and type of greenhouse gas (e.g. methane, perfluorocarbons, and nitrous oxide) CO_2e signifies the concentration of CO_2 which would have the same amount of radiative forcing.
SOURCE: UNEP, 2017.

would be deployment of \$100/t CO_2 NETs to capture and store 2.5 kg of CO_2 for each liter of aviation fuel consumed.[1] This will add ~25 cents per liter of fuel. This is just one example of how NETs might be conceptually bundled with emissions sources that are difficult to eliminate.

> **Conclusion 1: Negative emissions technologies are best viewed as a component of the mitigation portfolio, rather than a way to decrease atmospheric concentrations of carbon dioxide only after anthropogenic emissions have been eliminated.** The central question is "which is least expensive and least disruptive in terms of land and other impacts—an emission reduction or an equivalent amount of negative emission?" The committee recognizes that there is a possibility that large negative emissions in the future could result in a moral hazard, by reducing humanity's will to cut emissions in the near term. Reducing emissions is vital to addressing the climate problem. However, the least expensive and least disruptive solution involves a broad portfolio of technologies, including those with positive, near-zero, and negative emissions. In addition, a broad portfolio of technologies (including multiple NETs) improves the ability to manage unexpected risks from nature and mitigation actions.

TECHNOLOGIES CONSIDERED

As directed by the Statement of Task, the committee focused on six major technical approaches to CO_2 removal and sequestration:

- **Coastal blue carbon** (Chapter 2)—Land use and management practices that increase the carbon stored in living plants or sediments in mangroves, tidal marshlands, seagrass beds, and other tidal or salt-water wetlands. These approaches are sometimes called "blue carbon" even though they refer to coastal ecosystems instead of the open ocean.
- **Terrestrial carbon removal and sequestration** (Chapter 3)—Land use and management practices such as afforestation/reforestation, changes in forest management, or changes in agricultural practices that enhance soil carbon storage ("agricultural soils").
- **Bioenergy with carbon capture and sequestration** (Chapter 4)—Energy production using plant biomass to produce electricity, liquid fuels, and/or heat combined with capture and sequestration of any CO_2 produced when using the bioenergy and any remaining biomass carbon that is not in the liquid fuels.

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[1] Combustion of a gallon of gasoline releases approximately 10 kg of CO_2 to the atmosphere.

- **Direct air capture** (Chapter 5)—Chemical processes that capture CO_2 from ambient air and concentrate it, so that it can be injected into a storage reservoir.
- **Carbon mineralization** (Chapter 6)—Accelerated "weathering," in which CO_2 from the atmosphere forms a chemical bond with a reactive mineral (particularly mantle peridotite, basaltic lava, and other reactive rocks), both at the surface (ex situ) where CO_2 in ambient air is mineralized on exposed rock and in the subsurface (in situ) where concentrated CO_2 streams are injected into ultramafic and basaltic rocks where it mineralizes in the pores.
- **Geologic sequestration** (Chapter 7)—CO_2 captured through BECCS or direct air capture is injected into a geologic formation, such as a saline aquifer, where it remains in the pore space of the rock for a long time. This is not a NET, but rather an option for the sequestration component of BECCS or direct air capture.

The exclusive focus of this report on terrestrial and near-shore coastal NETs reflects the Statement of Task. The committee recognizes that oceanic options for CO_2 removal and sequestration (e.g., iron fertilization and ocean alkalinization), which fall outside the scope of its task, could sequester an enormous amount of CO_2 and that the United States needs a research strategy to address them. The report also does not address mitigation options such as enhanced energy efficiency, renewable electricity, or reduced deforestation because they are not NETs. Their exclusion is not a statement about priorities. Reducing emissions is vital to addressing the climate problem. Policymakers should consider the broadest possible portfolio of technologies to find the most inexpensive and least disruptive solutions, including those with positive, near-zero, and negative emissions.

CARBON REMOVAL POTENTIAL AND NEED

The committee identified the potential rates of CO_2 removal and sequestration that could be achieved safely and economically, given our current knowledge and level of technological development. These results are summarized in Table S.1 and expanded in Tables 8.1 and 8.2. "Safe" means that the deployment would, with high confidence, not cause the large potential adverse societal, economic, and environmental impacts that are described in detail in each report chapter. "Economical" means that the deployment would cost[2] less than \$100/t CO_2. Most of the NETs that meet that criterion actually cost less than \$20/t CO_2. Differences among rows in the significant digits listed reflect heterogeneity in the state of knowledge. It is important to understand

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[2] The committee refers to direct costs of attaining negative emissions (e.g., operating costs, labor costs). It recognizes that all NETs have a full set of indirect costs (e.g., impact on land values) that may not be reflected in direct cost estimates.

TABLE S.1 Cost, Limiting Factors, and Impact Potential of NETs with Current Technology and Understanding. "Safe" maximum rate of CO_2 removal means that the deployment would not cause large potential adverse societal, economic, and environmental impacts. These estimated rates assume full adoption of agricultural soil conservation practices, forestry management practices, and waste biomass capture.

Negative Emissions Technology	**Estimated Cost** (\$/t CO_2) L = 0 - 20 M =20 -100 H = >100	**Safe Potential Rate of CO_2 Removal Possible Given Current Technology and Understanding and at ≤\$100/t CO_2** (Gt/y CO_2)		**Primary Current Limiting Factors**
		US	Global	
Coastal blue carbon	L	0.02	0.13[a]	• Available land given coastal development and land use • Understanding of future rates with sea level rise and coastal management
Terrestrial carbon removal and sequestration: afforestation/ reforestation	L	0.15	1	• Available land given needs for food and fiber production and for biodiversity • Inability to fully implement forestry management practices
Terrestrial carbon removal and sequestration: forest management	L	0.1	1.5	• Demand for wood limits feasible reduction in harvest rate, though some forest management activities would not impact fiber supplies • Inability to fully implement forestry management practices
Terrestrial carbon removal and sequestration: agricultural practices to enhance soil carbon storage	L to M	0.25	3	• Limited per-hectare rates of carbon uptake by existing agricultural practices • Inability to fully implement soil conservation practices

TABLE S.1 Continued

Bioenergy with carbon capture and sequestration (BECCS)	M	0.5	3.5-5.2	• Cost • Availability of biomass given needs for food and fiber production and for biodiversity • Inability to fully capture waste biomass • Fundamental understanding
Direct air capture	H	0^b	0^b	• Cost is greater than economic demand • Practical barriers to pace of scale up
Carbon mineralization	M-H	unknown	unknown	• Fundamental understanding, especially of feedbacks between carbon mineralization and permeability for *in situ* methods
Total		1.02	9.13-10.83	

NOTE: Number of significant digits reflects state of knowledge among different NETs and between US and global estimates.

[a] Global removal rate based on coastal wetland area lost since approximately 1980 and annual burial rate with restoration; does not include active management of existing areas or managed wetland transgression.

[b] Cost for deployed air capture remains substantially above \$100/t CO_2 (as high as \$600/t CO_2).

that safe and economical limits to NET deployment are not necessarily achievable in a practical sense, because human behavior, logistical shortages, organizational capacity, and political factors can also limit deployment.

The collection of NETs in Table S.1 exhibit a wide range of technical maturity. Some approaches to carbon removal, such as reforestation, have been developed over many decades and are already deployed at large scale. Others, such as several types of enhanced carbon mineralization, are at the early stages of exploration by academic researchers and have never been tried in the field. In general, the cost estimates for technologies that have not been demonstrated are more speculative than those for technologies that have been deployed at scale. However, even NETs that are relatively mature will benefit from additional research to reduce costs and negative impacts and to increase co-benefits.

There are also fundamental differences among the primary factors that limit potential rates and capacities of NETs. Land-based NETs, especially afforestation/reforestation and BECCS, are constrained by land availability, because of competing needs to produce food and preserve biodiversity and by the responses of landowners to incentives. Research on land-based options would help to ensure that the capacities listed in Table S.1 can be realized or increased as discussed in Chapter 8, but their potential will remain limited by available land. In contrast, the major barrier to large-scale direct air capture is the high current cost. If made less expensive, direct air capture technologies could be scaled up to remove very large amounts of carbon. Finally, carbon mineralization is currently constrained by many scientific unknowns, as well as uncertainty about environmental impacts and likely cost. However, like direct air capture, carbon mineralization technologies could have very large capacity if their costs and environmental impacts could be sufficiently reduced. The analysis in Table S.1 leads to the committee's most important conclusions about the readiness of NETs:

Conclusion 2: Four negative emissions technologies are ready for large-scale deployment: afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and bioenergy with carbon capture and storage (BECCS). These NETs have low to medium costs (\$100/t CO_2 or less) and substantial potential for safe scale-up from current deployment. They also provide co-benefits including:

- increased forest productivity (changes in forest management);
- improved agricultural productivity, soil nitrogen retention, and soil water holding capacity (enhanced uptake and storage by agricultural soils); and
- liquid fuel production and electricity generation (BECCS).

Including combustion-based BECCS as being ready for large-scale deployment implies that the committee believes that geologic sequestration is ready for large-scale deployment.

Conclusion 3: Current negative emissions technologies with direct costs that do not exceed \$100/t CO_2 can be safely scaled up to capture and store substantial amounts of carbon, but significantly less than ~1 Gt/y CO_2 in the United States and ~10 Gt/y CO_2 globally. These levels represent a substantial fraction of the total emissions of ~6.5 Gt CO_2e in the United States and more than 50 Gt CO_2e globally, but they may be difficult to attain because they require unprecedented rates of adoption of agricultural soil conservation practices, forestry management practices, and waste biomass capture. Many past programs to induce landowners to change forest, grazing, and cropland management were not successful. Research may help to improve adoption levels, but this is uncertain. Also, approximately half the 1 Gt/y CO_2 in the US and 10 Gt/y CO_2 globally would be achieved with BECCS fueled exclusively with biomass waste, and would require the collection and delivery of all economically available agricultural, forestry, and municipal waste to a BECCS facility able to use that type of waste. This would be logistically challenging anywhere, and especially in countries with limited organizational capacity. It is thus important to understand that "substantially less than 1 Gt/y CO_2 in the US and 10 Gt/y CO_2 globally" means that achievable limits could be smaller by a factor of two or more.

Nonetheless, the potential global uptake from current technologies of significantly less than 10 Gt/y CO_2 is substantially lower that the negative emissions in most scenarios that would produce less than 2°C of warming, according to virtually every recent assessment (Chapter 8). For example, Figure S.1 shows net anthropogenic emissions of all greenhouse gases falling from more than 50 Gt CO_2e today to less than 20 Gt CO_2e at midcentury and to approximately zero by 2100. Approximately 10-20 Gt CO_2e of gross anthropogenic emissions come from sources that would be very difficult or expensive to eliminate, including a large fraction of agricultural methane and nitrous oxide. Most scenarios that meet the Paris agreement, such as the one in Figure S.1, thus rely on CO_2 removal and storage that ramps up rapidly before midcentury to reach approximately 20 Gt CO_2 by century's end.

> **Conclusion 4:** **If the goals for climate and economic growth are to be achieved, negative emissions technologies will likely need to play a large role in mitigating climate change by removing ~10 Gt/y CO_2 globally by midcentury and ~20 Gt/y CO_2 globally by the century's end.**

FACTORS AFFECTING SCALE UP

The committee considered a range of factors that will affect the scale-up of NETs. Described in detail in Chapters 2-7, these factors include the availability of land given the competing needs for food and biodiversity preservation, other environmental constraints, energy requirements, high cost, practical barriers, permanence, monitoring and verification, governance, and insufficient scientific or technological understanding. They helped to inform development of the recommended research program for each NET. Collectively, Conclusions 2-4 are critical, because they demonstrate that all existing safe and economical NETs and mitigation options together do not have sufficient capacity to meet the Paris agreement. Uncertain research breakthroughs will be required before those NETs can provide even the minority share of the solution in Conclusion 6. Any argument to delay mitigation efforts because NETs will provide a backstop drastically misrepresents their current capacities and the likely pace of research progress.

The Land Constraint

Because food demand is expected to double by mid-century, repurposing a significant amount of current agricultural land to produce feedstocks for BECCS or for afforestation/reforestation might have a significant effect on food availability and food prices, with far-reaching effects on national security and biodiversity. If afforestation/reforestation and BECCS could be extended to hundreds of millions of hectares of arable land without disrupting the food supply or causing the clearance of remaining tropical forests, then these options could deliver more than 10 Gt/y CO_2 of negative emissions. However, such an extension would require either a revolutionary breakthrough in agricultural productivity or revolutionary changes in diets (with greatly reduced meat consumption) and reduced food waste. Until research proves otherwise, it is prudent to view as impractical upper bounds for afforestation/reforestation and BECCS deployment of much greater than 10 Gt/y CO_2.

Other Environmental Constraints

Environmental concerns vary among the NETs. Because forests established at high latitudes decrease albedo, afforestation/reforestation at high latitudes would cause net warming despite the cooling caused by the forest's CO_2 uptake. In addition, forests established in regions with limited rainfall would have adverse effects on streamflow, irrigation, and groundwater resources. Mining minerals that spontaneously bind CO_2 would create enormous volumes of waste rock that may contaminate water and/or air. Approaches that enhance carbon uptake and storage in agricultural soils generally have large positive side benefits, including increased productivity, water holding capacity, stability of yields, and nitrogen use efficiency, but sometimes increase nitrous oxide emissions. Afforestation/reforestation, BECCS, and potentially some direct air capture routes may have substantial water requirements. In particular, irrigated bioenergy crops may lead to a trade-off between land and water requirements, in addition to freshwater ecosystem degradation and biodiversity loss.

Energy Requirements

Direct air capture and some carbon mineralization options require a large energy input per ton of CO_2 captured, which increases costs. Direct air capture systems require between 5 and 10 GJ to capture a ton of atmospheric CO_2. To put this into perspective, combustion of 100 gallons of gasoline releases about 13 GJ of energy and emits about a ton of CO_2. Gt-scale direct air capture thus necessitates an enormous increase in low- or zero-carbon energy to meet energy demands, which would compete with use of such energy sources to mitigate emissions from other sectors.

High Cost

The primary impediment to several NETs is high cost. Climeworks, which has the only existing commercial direct air capture machine, captures CO_2 at a reported cost of \$600/t CO_2. The estimated cost of capture and sequestration for BECCS systems that produce electricity is \$70/t CO_2, which is higher than costs for capture and sequestration from fossil fuel electricity. Although costs for direct air capture and BECCS may decline quickly, they are not currently competitive. The costs of carbon mineralization are uncertain because the fundamental understanding of the processes and engineering systems required for effective sequestration is insufficient.

Practical Barriers

Implementing NETs at the scale necessary to limit warming to 2°C presents practical barriers. For example, a 10 percent per year increase from the 65 Mt/y CO_2e that is currently injected underground for CO_2-enhanced oil recovery and saline aquifer sequestration is needed in order to scale up underground injection for geological sequestration. Comparable or greater rates will be required of every available NET. At these rates, scale-up could be limited by materials shortages, regulatory barriers, infrastructure development (i.e., CO_2 pipelines and renewable electricity), the availability of trained workers, and many other barriers.

Furthermore, humans often resist actions that appear to be in their economic interest. For example, historical adoption rates of agricultural soil conservation and forestry management practices that would save farmers and forest landowners money have been surprisingly low, as have dietary changes, such as reduced meat consumption, that would increase health while freeing agricultural land for forestry NETs and BECCS. These behaviors could limit deployment of NETs, as could public resistance to new local infrastructure, but they are not well represented in integrated assessment models.

Permanence

The terrestrial and coastal blue carbon options are reversible if the carbon sequestering practices are not maintained. For example, forested land could be cleared again, reverting to intensive tillage will eventually reverse soil carbon gains from reduced tillage in agricultural soils, or a restored coastal wetland could be drained again. Although temporary CO_2 storage will have some climate benefit, scientific and economic requirements to ensure the permanence of storage within ecosystems are substantial. In contrast, BECCS, direct air capture, and carbon mineralization have comparatively minor issues of permanence. CO_2 that is geologically sequestered can leak from saline aquifers but at rates low and straightforward enough to remediate. Permanence for carbon mineralization would be very high for mineralization of basalt or peridotite.

Monitoring and Verification

Monitoring and verification will be critical components of any large-scale deployment of NETs. Terrestrial carbon removal and sequestration approaches are sufficiently well understood that, in most cases, they could be deployed in the United States with remote monitoring and verification backed up by onsite measurements in a statistical sample. Effective monitoring and verification will require improved systems to monitor forest carbon and soil carbon on agricultural lands, expanded remote sensing of land use and management practices, better integration of existing data sets and models, and selected improvements in global monitoring to help address "leakage" (i.e., land-use changes in one location inducing land-use changes in other locations). Coastal blue carbon could be monitored and verified inexpensively through remote methods, although landscape heterogeneity would require finer resolution than terrestrial approaches, backed up by onsite measurements of a statistical sample. Because most carbon mineralization efforts would store CO_2 in inert and essentially permanent solid form, they might have the lowest monitoring and verification costs of all the NETs. This is particularly true for in situ carbon mineralization, whereas dispersal of reactive rock material in soil, along beaches, or into the shallow ocean could be as difficult, or more difficult, to verify than enhancements to agricultural soil carbon. Monitoring and verification of direct air capture would be straightforward because the amount of CO_2 can be directly measured. Monitoring and verification of sequestration in saline aquifers requires sophisticated methods such as seismic imaging, measuring pressure in and above the sequestration reservoir, and routine measurements of well integrity.

Governance

Appropriate governance of NETs and sequestration is critical because overly lax oversight would lead to ineffective CO_2 removal and loss of public confidence, while overly strict oversight would limit deployment. Governance is especially critical when large-scale deployment is imminent. Currently, governance is well established only in those sectors covered by a national or international agreement, including afforestation/reforestation (under the United Nations Framework Convention on Climate Change) and saline aquifer storage (under the Underground Injection Protocol of the Safe Water Drinking Act). In addition, the United States and other governments have ample experience regulating agriculture and forestry for non-NET purposes. One way to maintain public confidence during rapid deployment of NETs is to invest in a substantial effort to educate the public during the research and development stage.

Insufficient Scientific/Technical Understanding

Significant scientific gaps remain for all NETs, but especially for carbon mineralization and coastal blue carbon. Regarding the former, there is limited understanding of the kinetics of CO_2 uptake, no inventory of appropriate geologic deposits and existing tailings of reactive but unreacted rock, and no technical expertise to manage tailings piles so that they effectively take up CO_2. In addition, negative feedbacks cannot be predicted, nor can the long-term consequences of depositing crushed reactive minerals in agricultural soils, along the coasts, or into the shallow ocean. For the latter, many of the critical processes that govern carbon burial and sequestration in coastal ecosystems lack a mechanistic understanding of how they may change under high rates of sea-level rise and other direct and indirect impacts of climate change, and few studies have been performed on transgression of coastal wetlands inland.

PROPOSED RESEARCH AGENDA

Scaling the capacity of NETs to address the expected needs for carbon removal will require a concerted research effort to address the constraints that currently limit deployment. The research agenda should address not only potential research gaps, but also other needs for scale-up of NETs including cost reductions, deployment, and monitoring/verification. Based on its review of the factors that will affect scale-up of NETs, the committee drew the following conclusions that motivate the selection of research priorities:

> **<u>Conclusion 5:</u> Afforestation/reforestation, agricultural soils, forest management, and BECCS can already be deployed at significant levels but limited per-hectare rates of carbon uptake by agricultural soils and competition with food and biodiversity for land (for afforestation/reforestation, forest management, and BECCS) will likely limit negative emissions from these options to significantly less than 10 Gt/y CO_2, globally.** Research could identify ways to soften the land constraint, for example by developing crop plants that take up and

sequester carbon more efficiently in soils, or by reducing demand for meat or food waste. However, crop improvement is a slow process, while meat consumption and food waste remain high despite health and economic drivers to reduce them.

Conclusion 6: Direct air capture and carbon mineralization have high potential capacity for removing carbon, but direct air capture is currently limited by high cost and carbon mineralization by a lack of fundamental understanding.

Conclusion 7: Although their potential for removing carbon is lower than other negative emissions technologies, coastal blue carbon approaches warrant continued exploration and support. The cost of the carbon removal is low or zero because investments in many coastal blue carbon projects target other benefits such as ecosystem services and coastal adaptation. Understanding of the impacts of sea-level rise, coastal management, and other climate impacts on future uptake rates should be improved.

Conclusion 8: Several carbon mitigation research efforts would also support the advancement of negative emissions technologies. Research on geologic storage of carbon dioxide is critical to improve decarbonization of fossil fuel power plants, and also critical for advancing direct air capture and BECCS. Similarly, research on biofuels would also advance BECCS.

The committee developed a detailed research agenda that is divided into two categories: 1) projects that would exclusively advance NETs (Table S.2); and 2) NET-enabling research on biofuels and CO_2 sequestration that should be undertaken as part of an emissions mitigation research portfolio (Table S.3). Drawing on the expertise of certain members, the committee estimated the budget for each research effort, which could be funded across a range of agencies (described further in Chapters 2-7). Of course, these budget estimates contain some uncertainty, but there is value in assessing the relative levels of investment needed to advance each of the NETs and sequestration approaches. For example, the estimated research budget for afforestation/reforestation and forest management is lower than that for other NETs because these approaches are more mature. In contrast, the estimated research budgets for carbon mineralization and direct air capture are larger because these technologies are relatively new and underexplored. The committee also identified an appropriate timespan to fund and conduct each effort. In many cases, the research should be conducted in stages—that is, funding will continue if certain milestones are met.

The scale of these research costs is commensurate with the size of the carbon and climate problem. A solution such as the one depicted in Figure S.1 requires electricity

TABLE S.2 Research Plan and Budget for Negative Emissions Technologies Plus Sequestration (abbreviated from Table 8.3)

NET	Research Title	Cost $/y	Duration Years
Coastal	Basic research in understanding and using coastal ecosystems as a NET	6M	5-10
	Mapping current and future (i.e., after sea level rise) coastal wetlands.	2M	20
	Integrated network of coastal sites for scientific and experimental work on carbon removal and storage.	40M	20
	National Coastal Wetland Data Center, including data on all restoration and carbon removal projects.	2M	20
	Carbon-rich NET demonstration projects and field experiment network	10M	20
	Coastal blue carbon project deployment.	5M	10
Afforestation/ Reforestation, Forest Management	Monitoring of forest stock enhancement projects	5M	≥3
	Forest demonstration projects: increasing collection, disposal, and preservation of harvested wood; and forest restoration	4.5M	3
Afforestation/ Reforestation, Forest Management, BECCS	Integrated Assessment Modeling and regional life cycle assessment of BECCS mitigation potential and secondary impacts	3.7-14M	10

continued

TABLE S.2 Continued

NET	Research Title	Cost $/y	Duration Years
Forest Management	Preservation of harvested wood	2.4M	3
	Research on greenhouse gases and social impacts of reducing traditional uses of biomass for fuel	1M	3
	Social sciences research on improving landowner responses to incentives and equity among landowner classes	1M	3
Agricultural Soils	National agricultural soils monitoring system	5M	Ongoing
	Experimental network improving agricultural soil carbon processes.	6-9M	≥12
	Data-model platform for predicting and quantifying agricultural soil carbon removal and storage	5M	5
	Scaling up agricultural soils sequestration activities	2M	3
	High carbon input crop phenotypes	40-50M	20
	Soil carbon dynamics at depth	3-4M	5
Agricultural Soils, BECCS	Biochar studies	3M	5-10
Agricultural Soils, Carbon Mineralization	Reactive mineral additions to soils	3M	10
BECCS	Biomass-to-fuel with biochar	40-103M	10

TABLE S.2 Continued

NET	Research Title	Cost $/y	Duration Years
Direct Air Capture	Basic research and early phase technology development	20-30M	10
	Independent techno-economic analysis, third-party materials testing and evaluation, and pubic materials database	3-5M	10
	Scaling-up and testing air capture materials and components	10-15M	10
	Third-party professional engineering design firm assistance for the above effort, including independent testing, and a public database	3-10M	10
	Design, build, and test pilot air capture system (>1,000 t/y CO_2)	20-40M	10
	National air capture test center support of pilots	10-20M	10
	Design, build, and test air capture demonstration system (>10,000 t/y CO_2)	100M	10
	National air capture test center support of demonstrations	15-20M	10

continued

TABLE S.2 Continued

NET	Research Title	Cost $/y	Duration Years
Carbon Mineralization	Basic research on mineralization kinetics	5.5M	10
	Basic research on rock mechanics, numerical modeling, and field studies	17M	10
	Mapping reactive mineral deposits and existing tailings (scoping for pilot studies)	7.5M	5
	Surficial (ex situ) carbon removal pilot studies	3.5M	10
	Medium-scale in-situ field experiment in peridotite rock	10M	10
	Development of a resource database for carbon mineralization	2M	5
	Studying the environmental impact of mineral addition to terrestrial, coastal and marine environments	10M	10
	Examining the social and environmental impact of an expanded extraction industry for the purpose of CO_2 removal	5M	10

TABLE S.3 Research Plan and Budget for NET-Enabling Research (abbreviated from Table 8.4)

NET	Research Title	Cost $/y	Duration Years
BECCS	Biomass-to-power with carbon capture and sequestration: biomass supply and logistics	53-123M	5
	Biomass-to-power with carbon capture and sequestration: high-efficiency biomass power	39-94M	10
	Biomass-to-fuel with carbon capture and sequestration	Ongoing research efforts are sufficient	
Carbon Mineralization	Mine tailings and industrial wastes	1M	10
	Medium-scale field in situ experiment in a basalt formation.	10M	10
Geologic Sequestration: Saline Aquifer Storage	Reducing seismic risk	50M	10
	Increasing the efficiency and accuracy of site characterization and selection	45M	10
	Improving monitoring and lowering costs for monitoring and verification	50M	10
	Improving secondary trapping prediction and methods to accelerate secondary trapping	25M	10
	Improving simulation models for performance prediction and confirmation.	10M	10
	Assessing and managing risk in compromised storage systems.	20M	10

continued

TABLE S.3 Continued

NET	Research Title	Cost $/y	Duration Years
Geologic Sequestration: Oil and Gas Field Sequestration	Developing reservoir engineering approaches for co-optimizing CO_2-EOR and sequestration	50M	10
Geologic Sequestration	Social sciences research to improve public engagement effectiveness with local communities and the general public	1M	10

NOTE: All projects listed above not only support the advancement of NETs, but should also be part of any comprehensive research effort on carbon mitigation.

generated by wind, solar, biomass, nuclear, and natural gas with carbon capture and sequestration; biofuels and electricity for transportation; and some form of energy storage. Every one of these technologies has already received large government investment. For example, a recent Congressional Research Service report *Renewable Energy R&D Funding History: A Comparison with Funding for Nuclear Energy, Fossil Energy, and Energy Efficiency R&D* estimates that the federal government spent more than $22 billion on renewable energy research and development from 1978 to 2013. NETs have not received comparable public investment despite expectations that they might provide ~30 percent of the net emissions reductions required this century (i.e., maxima of 20 Gt/y CO_2 of negative emissions and 50 Gt/y CO_2 of mitigation in Figure S.1). NETs are essential to offset greenhouse gas emissions that cannot be eliminated, such as a large fraction of agricultural nitrous oxide and methane emissions. Inexpensive direct air capture or carbon mineralization could allow for some continued use of fossil fuels without impacting climate. Recent regulatory proposals to freeze light-duty fuel economy standards over the 2021-2025 period and changes to the Clean Power Plan may further the need for NETs. Table S.3 contains a proposed budget for improving CO_2 sequestration in saline aquifers and for enhanced oil recovery. This information is included because CO_2 sequestration is required by direct air capture and BECCS, but the size of the budget reflects the larger need for sequestration of CO_2 captured at other energy sources such as fossil fuel electricity plants. The scale of the recommended research budget is consistent with the need for NETs that can solve a substantial fraction of the climate problem.

> **Recommendation: The nation should launch a substantial research initiative to advance negative emissions technologies (NETs) as soon as practicable.**

A substantial investment would (1) improve existing NETs (i.e., coastal blue carbon, afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and bioenergy with carbon capture and sequestration) to increase the capacity and to reduce their negative impacts and costs; (2) make rapid progress on direct air capture and carbon mineralization technologies, which are underexplored but would have essentially unlimited capacity if the high costs and many unknowns could be overcome; and (3) advance NET-enabling research on biofuels and carbon sequestration that should be undertaken anyway as part of an emissions mitigation research portfolio.

CONCLUDING REMARKS

Recent analyses of economically optimal solutions to the climate problem have concluded that NETs will play as significant a role as any mitigation technology, with perhaps 10 Gt/y CO_2 of negative emissions needed approximately at midcentury and 20 Gt/y CO_2 by the century's end. Several Gt/y CO_2 of negative emissions at less than \$20/t CO_2 are already available. Nonetheless, existing options (coastal blue carbon, afforestation/reforestation, forest management, agricultural soils and BECCS) cannot yet provide enough negative emissions at reasonable cost, without substantial unintended harm. A substantial research investment is needed to improve existing NETs and to reduce their negative impacts and costs. In addition, direct air capture and carbon mineralization have essentially unlimited capacity and are almost unexplored.

The committee recognizes that the federal government has many other research priorities, including others in mitigation and adaptation to climate change. Multiple reasons exist to pursue research on NETs. First, states, local governments, corporations, and countries around the world are making substantial investments to reduce their net carbon emissions and plan to increase these investments. Some of these efforts already include negative emissions. This means that advances in NETs will benefit the U.S. economy if the intellectual property is held by U.S. companies. Second, as climate damages mount, the United States will inevitably take increased action to limit climate change in the future. Third, the United States is already making a substantial effort, including the new 45Q rule[3] that provides a tax credit of \$50/t CO_2 for capture and sequestration in saline aquifers and \$35/t CO_2 for oil and gas reservoirs, which would leverage the value of new investments in NET research. Thus, though climate mitigation remains the motivation for global investments in NETs, intellectual property and economic benefits will likely accrue to the nations that develop the best technology.

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[3] https://www.law.cornell.edu/uscode/text/26/45Q.

CHAPTER ONE

Introduction

As atmospheric concentrations of carbon dioxide (CO_2) have continued to increase, policymakers have confronted the need to not only reduce emissions, but also remove CO_2 from the atmosphere. This report assesses methods for creating or enhancing terrestrial and coastal carbon sinks for atmospheric CO_2. An anthropogenic carbon sink captures atmospheric CO_2 and then stores it in a reservoir, either in its captured form or another chemical form. Storage reservoirs can be either on or under the land surface, or in the ocean. This report considers only land and near-shore coastal reservoirs.

Anthropogenic CO_2 released to the atmosphere by fossil fuel consumption, land use change, and cement production is the dominant cause of current and projected future climate change. Removing CO_2 from the atmosphere and storing it has the same impact on the atmosphere climate as simultaneously preventing emission of an equal amount of CO_2. For this reason, methods that create or enhance carbon sinks are best considered as part of the toolkit for net CO_2 emissions reductions, although they are sometimes misleadingly classified with solar radiation management as "geo-engineering" (Budyko, 1977; NRC, 2015a, b; PSAC, 1965). Combustion of 1 gallon of gasoline releases approximately 10 kg of CO_2 to the atmosphere. Capturing 10 kg of CO_2 from the atmosphere and permanently sequestering it therefore has the same effect on atmospheric CO_2 as any mitigation method that simultaneously prevents combustion of 1 gallon of gasoline.

OVERVIEW

The committee repeatedly encountered the viewpoint that most CO_2 removal and sequestration[1] approaches, or negative emissions technologies (NETs), will be deployed to reduce atmospheric CO_2 after fossil emissions have been reduced to near zero. However, this viewpoint does not consider the fact that decreasing fossil emissions once they reach low levels will likely be very expensive and therefore methods for reduced and negative emissions will likely be used in concert for centuries, even during a sustained period of net negative global emissions (see Box 1.1, Figure A). Thus,

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[1] Although the term "storage" might imply accumulation for future use, the committee uses this term interchangeably with the term "sequestration" in accordance with the literature reviewed (Fuss et al., 2018).

BOX 1.1
OCEAN AND TERRESTRIAL SINKS

The dynamics of the ocean and terrestrial sinks are inherently more complicated than these simplified images and remain challenging to predict with models (Friedlingstein et al., 2014). Several global models predict that the terrestrial sink will eventually switch to a source under business-as-usual emissions due to warming-accelerated decomposition of organic matter in high-latitude soils, nutrient limitation of CO_2 fertilization, and forest die-back from heat, drought, and insect pests (Joos et al., 2001; Prentice et al., 2001). Similarly, the future size of the oceanic sink depends on changes in ocean circulation resulting from a host of factors, including the strong wind-speed dependence of CO_2 exchange between the atmosphere and surface ocean and the effects of warming and glacial melt water on the overturning circulation (DeVries et al., 2017; Sarmiento et al., 1998; Swart et al., 2014).

Figure A depicts the predicted carbon exchanges from six global models under the RCP (Representative Concentration Pathway) 2.6 scenario for future atmospheric greenhouse gas concen-

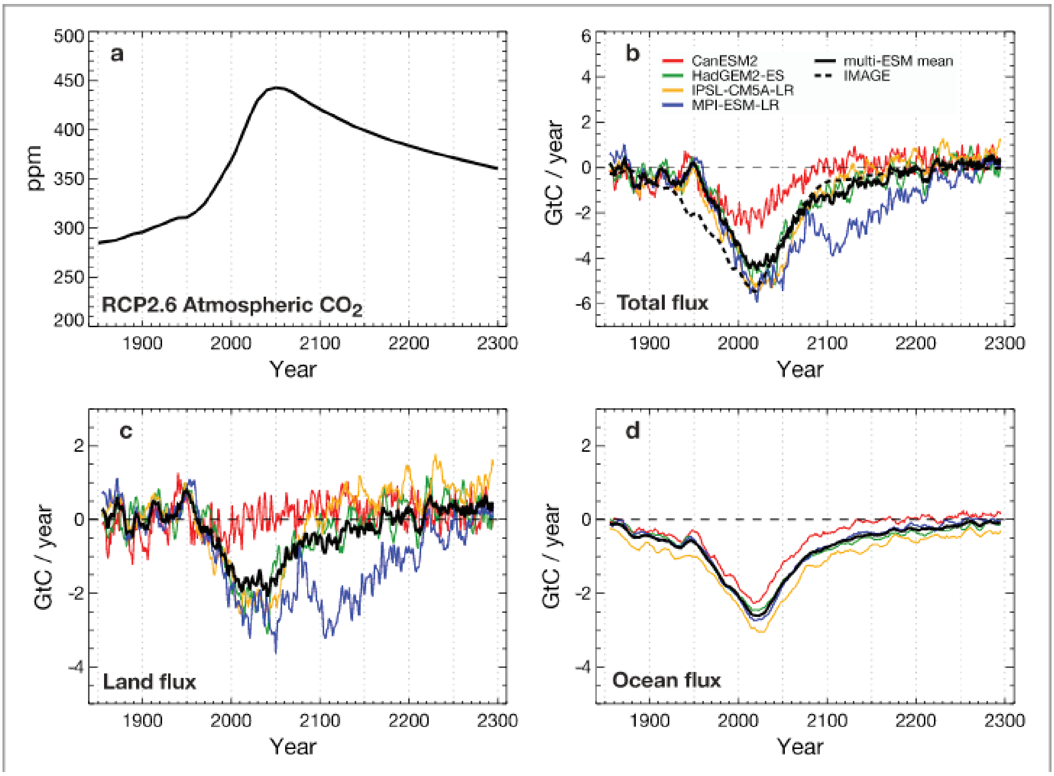

FIGURE A RCP2.6 scenario and simulated carbon fluxes. SOURCE: Jones et al., 2016.

BOX 1.1 Continued

trations, which produces less than 2°C of warming in the majority of climate models (Jones et al., 2016). In the top left panel of Figure A, the atmospheric concentration of CO_2 declines after modeled year 2050 by 82 ppm, from 450 ppm in 2050 to 368 ppm in 2300. The panels in Figure B show the anthropogenic emissions (brown) and sinks from NETs for four 50-year periods. The green and dark blue boxes show the predicted sizes of the "natural" land and ocean sinks, while the light blue boxes show the starting and ending atmospheric concentrations (the atmospheric concentration at the end of each period and the beginning of the next are mildly inconsistent because of small inconsistencies between the scenario and modeled predictions as described in the supplementary information of Jones et al., 2016).

The most unexpected aspect of Figure B is that the atmospheric concentration declines by 25 ppm or 196 Gt CO_2 from 2050 to 2100 (see upper right panel of), despite net anthropogenic

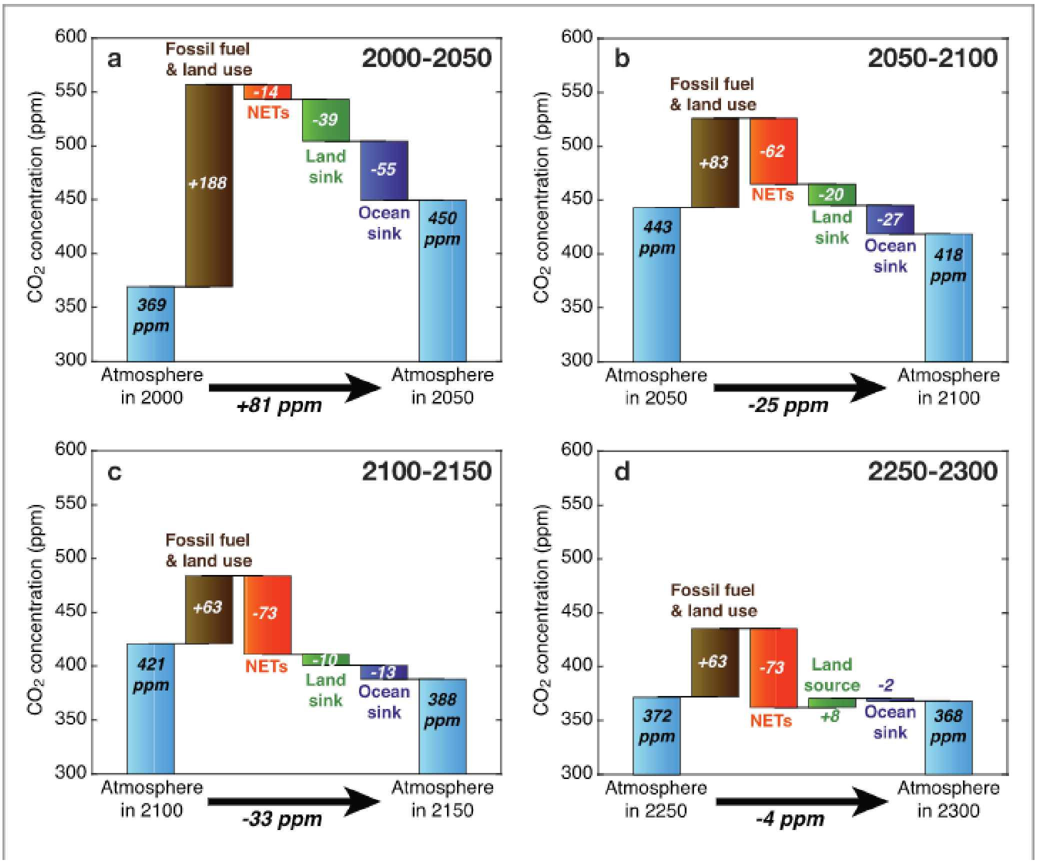

FIGURE B The four stages of succession of the differing balance between flux components. SOURCE: Jones et al., 2016.

continued

BOX 1.1 Continued

emissions of 164 Gt CO_2 during the same period (fossil and land use minus NET), because the land and ocean carbon sinks take up 196+164 Gt CO_2. The sinks persist for over a century of declining atmospheric CO_2 in Figure B, because the disequilibrium uptake of CO_2 by the long-lived carbon pools in the land and ocean models dominates out-gassing by the short-lived carbon pools. The 2050-2100 results imply that an identical 25 ppm reduction in atmospheric CO_2 could be achieved solely by reducing the fossil and land use emissions to 164 Gt CO_2, without any deployment of NETs. Similarly, over the 250-year period from 2050 to 2300 in Figure B, the large net ocean and land sink causes the atmospheric concentration to decline by 75 ppm, though net anthropogenic emissions are slightly positive.

At the same time, reducing the average 2050-2100 fossil fuel and land-use emissions to the ~3.3 Gt/y CO_2 in Figure B (less than 10 percent of today's emissions) would likely be very difficult without the use of NETs to offset emissions that would be prohibitively expensive or disruptive to eliminate, such as some agricultural methane and nitrous oxide (N_2O) emissions, or CO_2 emissions from air travel. In this sense then, NETs would be essential to achieving reductions in atmospheric CO_2 such as those in Figure B, because they would be essential to reducing net anthropogenic emissions enough so that remaining land and ocean sinks could reduce the atmospheric concentration. Moreover, it may become necessary to reduce atmospheric CO_2 beyond the capacity of natural sinks. NETs offer the only way to achieve such deep reductions.

the question remains "Which costs[2] more—an emission reduction or an equivalent amount of negative emission?"

> **<u>Conclusion 1:</u> Negative emissions technologies are best viewed as a component of the mitigation portfolio, rather than a way to decrease atmospheric concentrations of carbon dioxide only after anthropogenic emissions have been eliminated.**

For example, few alternatives to chemical fuels are likely to exist for commercial aviation. One option for zero net emissions would be to use a NET to capture and store the 2.5 kg of CO_2 for each liter of aviation fuel consumed. If the price of the NET could be reduced to \$100/t CO_2, then the cost of fuel would increase by ~\$0.25 per liter. The total CO_2 emissions of the fossil/NET bundle may decrease in comparison to cellulosic biofuels, without the carbon emissions associated with biofuels production and the negative externalities associated with devoting close to 100 million hectares of cropland to produce the required feedstock (Gunnarsson et al., 2018; Owen et al., 2010).

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[2] The committee refers to a comparison of direct costs of attaining an emissions reduction or negative emissions. All negative emissions and reduction technologies have a full set of indirect costs that may not be reflected in direct cost estimates.

As shown in the following chapters, some NETs are already cost-competitive with other mitigation options. Additional research would further reduce costs and facilitate scale-up. However, options with sufficient capacity to create negative emissions of at least 10 Gt/y CO_2 have large negative side-effects (i.e., the impact of large-scale reforestation and afforestation on food production and biodiversity), are not yet well enough understood to deploy at scale, and/or face competition with less expensive mitigation options, which impedes research and development (R&D) by the private sector.

For example, at current costs for direct air capture, it would be difficult for a direct air capture/fossil bundle to compete successfully in markets for renewable fuels, because direct air capture alone would add more than $1 per liter to the cost. A related problem is that direct air capture requires considerable input of electrical and heat energy. Given that available energy is largely derived from fossil fuel today, direct air capture with net negative CO_2 emissions may not become cost-competitive until low-cost zero-carbon energy is available. Finally, direct air capture must be coupled with reliable sequestration. The only existing method for sequestering large amounts of CO_2 is geologic sequestration, and current rates of geologic sequestration are much lower than what would be required to impact atmospheric concentrations.

Although several companies aim to commercialize direct air capture systems (e.g., Carbon Engineering, Global Thermostat, Climeworks), Climeworks is the furthest along in the market process, selling to a comparatively small market in high-cost CO_2 (i.e., CO_2 used in greenhouses to enhance productivity may cost more than $1,000/t if the greenhouse is located far from a source). This market is too small to support a robust ecosystem of small innovators necessary to explore the large number of chemical recipes and physical machinery that might decrease direct air capture prices. Thus, like photovoltaics or hydraulic fracturing and horizontal drilling, the development of direct air capture will likely require long-term government investment in incentives.

BACKGROUND ON THE CARBON CYCLE AND CARBON SINKS

Isotopic evidence shows that the increase in atmospheric CO_2 concentration from 280 parts per million (ppm) in 1750 to 407 ppm in 2017 was primarily caused by fossil fuel burning (IPCC, 2013; Le Quéré et al., 2016). Since 1750, 71 percent of the carbon atoms in anthropogenic CO_2 emissions have originated from geologic reservoirs of coal, oil, and natural gas, 2 percent from geologic reservoirs of limestone used in cement production, and 27 percent from terrestrial ecosystems—primarily because of the clearing of forests, draining of wetlands, and the conversion of forests and grasslands to croplands and pastures (see Figure 1.1). NETs can help to reverse these transfers, by

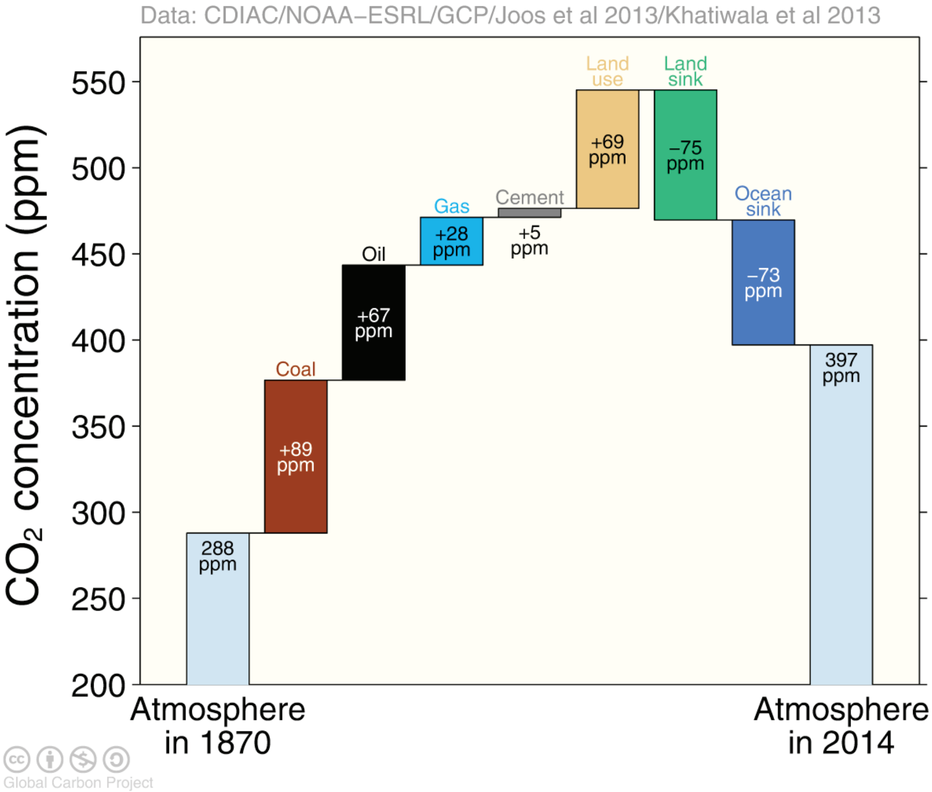

FIGURE 1.1 Cumulative contributions to the global carbon budget since 1870. NOTE: Contributions are shown in parts per million (ppm). SOURCE: Le Quéré et al., 2016.

removing CO_2 from the atmosphere and transferring it back to geologic reservoirs and ecosystems.

Figure 1.1 also shows that the increase in atmospheric CO_2 since the industrial revolution would have roughly doubled the observed ~125 ppm, if carbon sinks in the terrestrial biosphere and oceans had not taken up one-half of anthropogenic emissions. The "atmospheric fraction" (AF) is the annual increase in atmospheric CO_2 divided by total anthropogenic emissions. Despite substantial interannual variation, much of it linked to the El Niño–Southern Oscillation (ENSO) cycle, the multiyear average atmospheric fraction has remained remarkably steady at ~45 percent since continuous measurements of atmospheric CO_2 began in the late 1950s, indicating that the sum of land and ocean sinks has grown in proportion to anthropogenic emissions (see Figure 1.2). The land and ocean carbon sinks are often referred to as "natural" sinks, though a more appropriate adjective is probably "inadvertent," because they are unintended byproducts of fossil fuel consumption and land use. The growth of the land sink is thought to

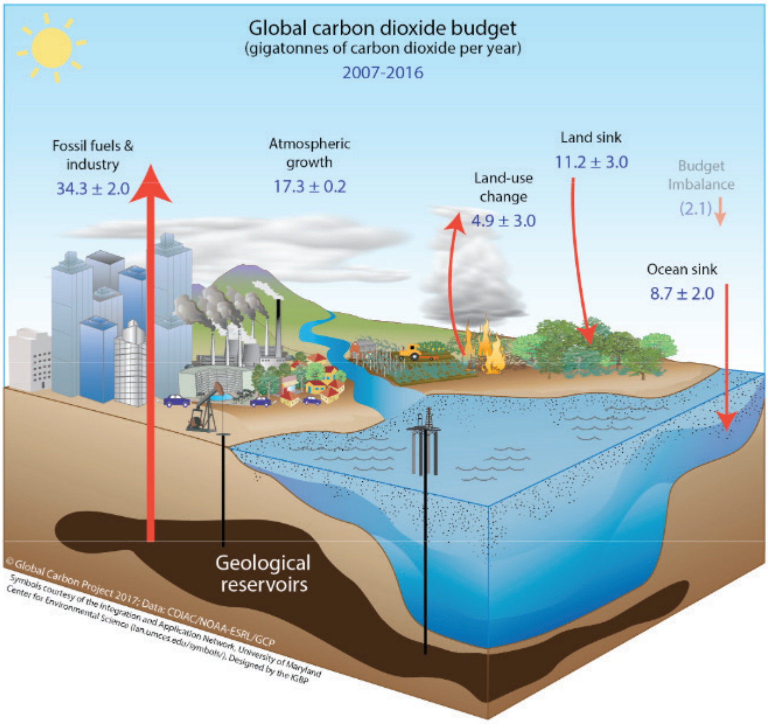

FIGURE 1.2 Global carbon dioxide budget.

NOTE: The global carbon budget refers to the mean, variations, and trends in the anthropogenic perturbation of CO_2 in the atmosphere since the beginning of the industrial era. It quantifies the input of CO_2 to the atmosphere by emissions from human activities, the growth of CO_2 in the atmosphere, and the resulting changes in land and ocean carbon fluxes in response to increasing atmospheric CO_2 levels, climate change and climate variability, and other anthropogenic and natural changes. SOURCE: Le Quéré et al., 2018.

have two primary causes: CO_2 fertilization of plants, which enhances photosynthesis and causes terrestrial ecosystems to gain carbon mass, and forest regrowth following agricultural abandonment in some locations (Pan et al., 2011). The ocean sink is caused both by the physical dissolution of atmospheric CO_2 and by photosynthetic carbon gain by phytoplankton (Figure 1.3; Sarmiento and Gruber, 2002).

To understand the effect of NETs on future CO_2 uptake by the "inadvertent" sinks, it is useful to divide the carbon sequestered by both the ocean carbon sink and the component of the land sink caused by CO_2 fertilization into two separate pools. These two pools are distinguished by their characteristic time scales for carbon retention. Some carbon sinks are quick to reach equilibrium with the atmosphere, whereas others will continue to remove atmospheric CO_2 over the next 10,000 years. Carbon in surface

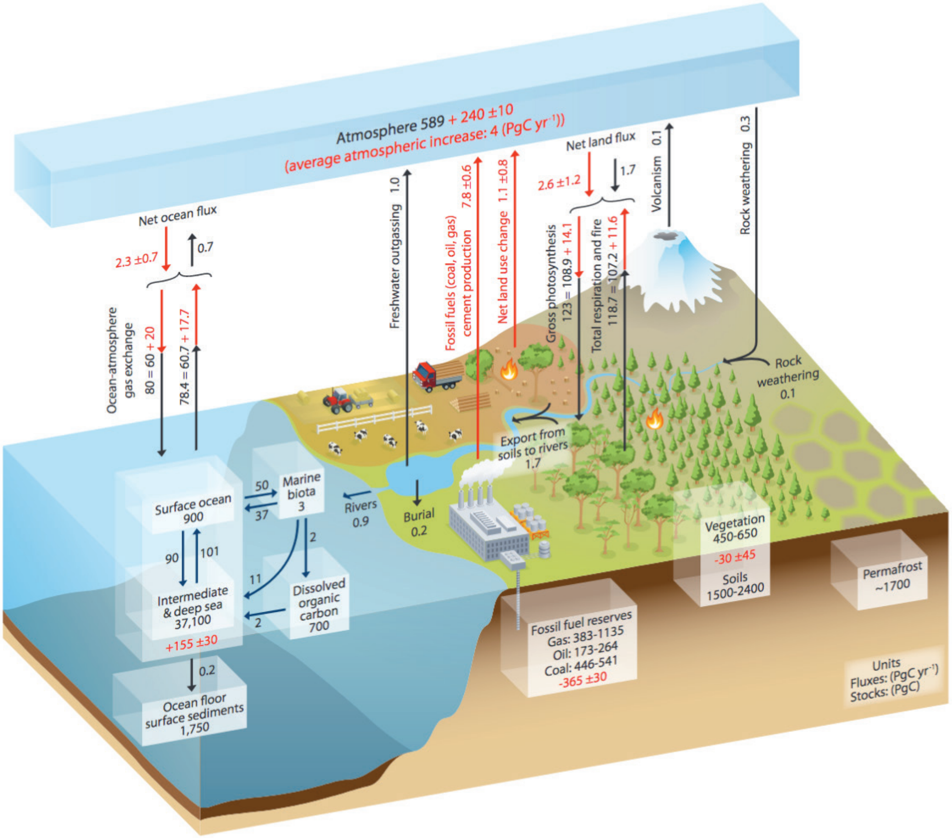

FIGURE 1.3 Schematic of the global carbon cycle.

NOTES: One PgC equals 1 billion metric tons of carbon (1 Gt C), which is the same amount of carbon as in 3.67 Gt CO_2. Further, 1 ppm CO_2 equals about 7.82 Gt CO_2. Black numbers show the cycle in 1750; red numbers show the average of 2000-2009. SOURCE: IPCC, 2013.

waters of the ocean (see Figure 1.3) and in short-lived and rapidly decomposing tissues on land (such as most of the carbon in leaves and fine roots) are carbon sinks that rapidly reach equilibrium with the atmosphere. As such, carbon in this short-lived pool is closely correlated to atmospheric CO_2, creating a sink whenever atmospheric CO_2 increases and a source whenever it decreases. Thus, the size of the sink correlates to the time-derivative of atmospheric CO_2. Carbon in the other pool has a long residence time, remaining out of equilibrium with atmospheric CO_2. This characteristic results from accumulation of the carbon in this pool in the past when the atmospheric concentration was lower, carbon in the deep ocean (residence time of ~1,000 years), and in living wood and recalcitrant dead organic matter on land (residence times of several decades to centuries). Rates of carbon addition to the long-lived pool increase with the gap between the current and past atmospheric CO_2 concentrations. The associated carbon sink can thus persist through a period of declining atmospheric CO_2, if the concentration remains sufficiently above the preindustrial concentration.

The results from Box 1.1 dispel two related scientific misunderstandings about NETs that the committee frequently encountered. The first is that NETs are qualitatively unlike other methods of climate mitigation because they offer society the only way to deliberately reduce the atmospheric concentration of CO_2. Instead, atmospheric CO_2 will decline once net anthropogenic emissions (emissions minus sinks from NETs) become smaller than the annual uptake by the natural sinks. At the same time, it would be extremely difficult to reduce net anthropogenic emissions enough to achieve declining atmospheric CO_2 without the use of NETs because some fossil and land-use sources would be extremely disruptive or expensive to mitigate, such as some agricultural methane or CO_2 from air travel. The same can be said of the omission of any major mitigation option, such as photovoltaics, wind electricity, or carbon capture and sequestration at fossil power plants. In addition, unlike other forms of mitigation, NETs provide the only means to achieve deep (i.e., >100 ppm) emissions reductions, beyond the capacity of the natural sinks. The second misconception is that the natural sinks would reverse and become sources during a period of declining atmospheric CO_2. Instead, the sinks are expected to persist for more than a century of declining CO_2 because of the continued disequilibrium uptake by the long-lived carbon pools in the ocean and terrestrial biosphere. For example, to reduce atmospheric CO_2 from 450 to 400 ppm, it would not be necessary to create net negative anthropogenic emissions equal to the net positive historical emissions that caused the concentration to increase from 400 to 450 ppm. The persistent disequilibrium uptake by the land and ocean carbon sinks would allow for achievement of this reduction even with net positive anthropogenic emissions during the 50 ppm decline.

Nonetheless, the strengths of the land and ocean sinks decline through time in Figure 1.4 because of the concerted effects of the rapid decline in the time-derivative of atmospheric CO_2 during the middle part of the century (for the rapidly equilibrating pools) and the declines in the absolute concentration after 2050 (for the disequilibrium pools). The mechanisms behind the sinks ensure that actions that decrease atmospheric CO_2 will also tend to decrease sink strength. Thus, based on the dynamics of the natural terrestrial and ocean sinks, the deployment of NETs will progressively reduce their effectiveness. The perturbation airborne fraction (PAF) plotted in Figure 1.4 represents the decrease in atmospheric CO_2 caused by the removal of one small unit

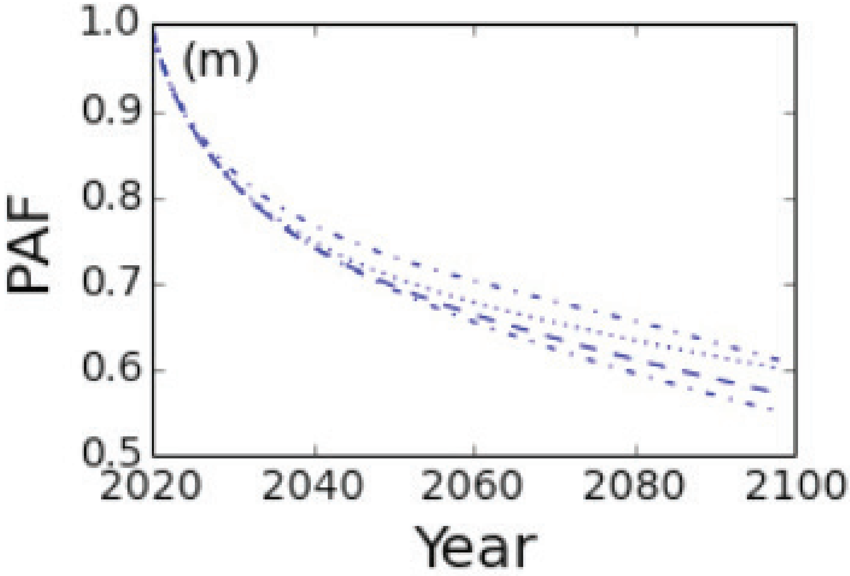

FIGURE 1.4 Perturbation airborne fraction in Jones et al., 2016.

of CO_2 by a NET. PAFs are less than 1.0 as the land and ocean sinks in the models are decreased by CO_2 removal, and the monotonic decrease through time from nearly 1.0 to almost 0.5 shows that effectiveness decreases progressively. At a PAF of 0.5, two units of negative emissions are required to achieve one unit of reduced atmospheric CO_2. However, this property is shared by technologies that reduce emissions; their use also weakens the sizes of the ocean and land sinks for the same reason.

This report focuses on the vital and productive role that NETs could play to reduce climate change immediately and throughout this century. The critical quantity here is net anthropogenic emissions, that is, the sum of positive emissions from fossil fuels and land use and negative emissions from NETs. The committee's goal is to propose research that will reduce the costs and disruption of NETs, and so allow deeper reductions in net anthropogenic emissions, or the same reductions at lower cost and with greater allowable emissions from fossil fuels and land use. In addition, research on NETs will provide humanity with the long-term option of very large reductions in atmospheric CO_2, like a return to preindustrial concentrations, although this is most likely a problem for the 22nd century (Hansen et al., 2017; Tokarska and Zickfeld, 2015).

ORIGIN AND PURPOSE OF THE STUDY

The United Nations Framework Convention on Climate Change (UNFCCC) pledged in 1992 to "prevent dangerous anthropogenic interference with the climate system" and initiated an international effort to reduce CO_2 emissions. Negative emissions technologies were brought into the framework of the UNFCCC by the Kyoto Protocol of 1997, which included reforestation and afforestation as part of its Clean Development Mechanism (UNFCCC, 2013). In the two decades since the Kyoto Protocol, scientific research has improved understanding of greenhouse gas concentrations and the amount of warming that would cause "dangerous anthropogenic interference with the climate system." Recent work (IPCC, 2012, 2013; NASEM, 2016) concludes that (1) damages from anthropogenic climate change are already occurring and will accelerate as greenhouse gases continue to accumulate and (2) under business as usual emissions, the climate system is in danger of crossing one or more thresholds for rapid and catastrophic change, such as multimeter sea-level rise from the loss of a major continental ice sheet.

The improved understanding of risks and damages created a consensus among many in the scientific community, nongovernmental organizations (NGOs), and governments that mean global warming should not exceed 2°C above the preindustrial value, and led to the Cancun agreement under the UNFCCC that committed governments to "hold the increase in average global temperature below two degrees" (UNFCCC, 2011). This in turn led to the adoption of Article 2 of the UNFCCC Paris agreement in 2016 by many nations of the world (although the United States has announced an intent to withdraw) to limit total warming below 2°C, and with an aspirational target of 1.5°C.

The 2°C target is exceedingly challenging—the global mean temperature has already risen about 1°C over the 20th century, and time lags in the carbon cycle and climate system likely mean that only about two-thirds of the warming that will eventually occur at current concentrations of atmospheric greenhouse gases has been reached (Hansen et al., 2011). The CO_2 concentration, currently 407 ppm (2017), would probably need to remain below 450 ppm to prevent more than 2°C of warming (IPCC, 2013). It is currently increasing at about 2 ppm per year (Figure 1.2, 7.82 Gt CO_2/ppm). Article 4 of the Paris agreement states that increases in atmospheric CO_2 should cease "in the second half of the century," although preventing the increase of atmospheric CO_2 does not require that anthropogenic emissions cease, only that they be less than or equal in strength to carbon sinks.

Studies using integrated assessment models (IAMs) conclude that the reduction in net anthropogenic emissions required to meet the 2°C target, let alone the 1.5°C target, would now be quite difficult and expensive to achieve, even with technological breakthroughs. For example, the projected costs of limiting atmospheric CO_2 below even 500 ppm average more than \$1,000/t CO_2 by 2100 in the IAM studies reviewed in the latest IPCC report (IPCC, 2014b). Moreover, the lowest cost trajectories for achieving the 2°C target chosen by the economic optimizations in IAMs often include massive deployment of NETs that would avoid the steeper costs of relying on emissions reductions alone. Some scenarios require that 600 million hectares of land (equal to nearly 40 percent of global cropland) be devoted to NETs (IPCC, 2014b). Net negative emissions in the second half of the century and beyond, achieved by the combined action of NETs, emissions reductions, and natural sinks, would allow atmospheric CO_2 to temporarily overshoot levels consistent with 1.5°C or 2°C of warming at equilibrium, as in the time-series of atmospheric concentrations in RCP 2.6 (Figure 1.5; Fuss et al., 2014). Because the time required to reach equilibrium temperature is extensive (centuries), subsequent reductions in atmospheric CO_2 could in principle keep global temperatures from exceeding the 1.5°C or 2°C target (Box 1.2.).

Improved understanding of future climate-related risks, coalescence around a 2°C target, and the prominence of NETs in the conclusions of IPCC (2014b) have led to substantial interest in negative emissions and to the recognition that far less is known about some NETs than about most traditional forms of carbon mitigation. In 2015, the National Academies published *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* (NRC, 2015b), which described and assessed relevant NETs and sequestration approaches and related concerns, including cost, technological readiness, required land, impacts on food production and biodiversity, required water, nitrogen and energy, permanence of stored carbon, far-field emissions of CO_2, emissions of non-CO_2 greenhouse gases, and biophysical impacts on climate (NRC, 2015b).[3] That report's recommendation for an R&D investment to minimize energy consumption and materials required by NETs, identify and quantify risks, reduce costs, and develop reliable sequestration and monitoring led to this current study. In addition, a recommendation from that report led to a related study on carbon use (see Box 1.3).

The specific charge to the committee is provided in Box 1.4. The study sponsors are the Department of Energy, National Oceanographic and Atmospheric Administration, Environmental Protection Agency, U.S. Geologic Survey, V. Kann Rasmussen Foundation, Incite Labs, and the Linden Trust for Conservation, with support from the National Academy of Sciences' Arthur L. Day Fund.

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[3] See also DOE, 2016, Socolow et al., 2011, and Tavoni and Socolow (2013).

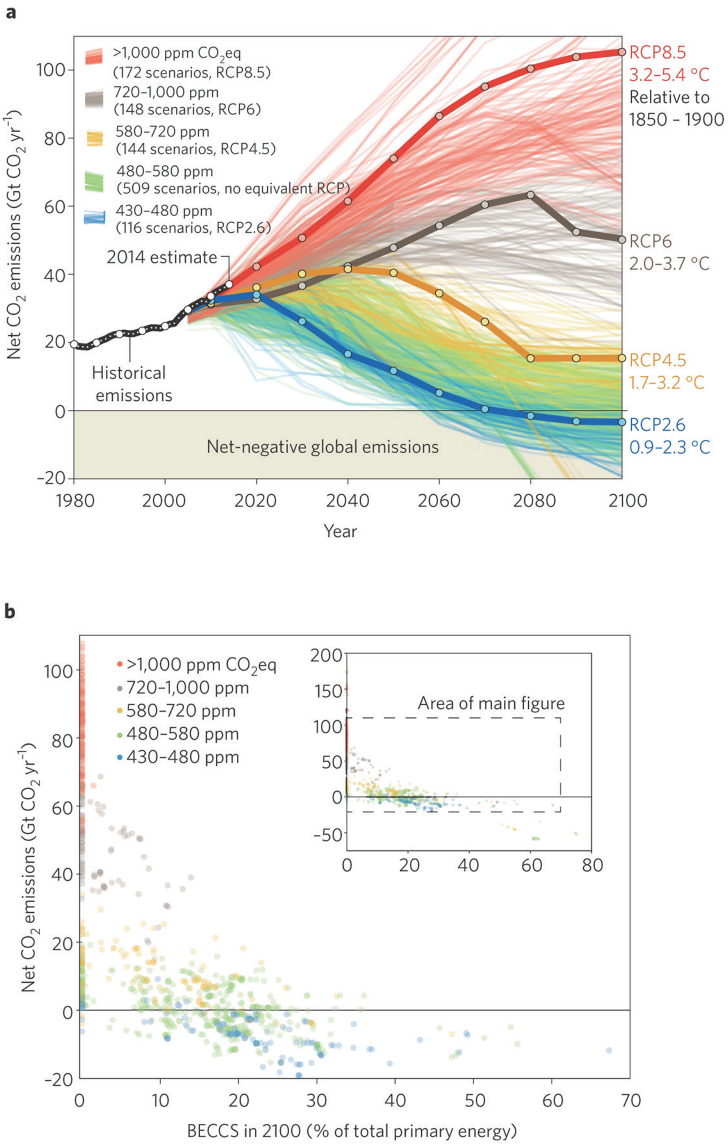

FIGURE 1.5 Panel a depicts CO_2 emission pathways until 2100, and panel b depicts the extent of net negative emissions and BECCS using RCP 2.6 in 2100. SOURCE: Fuss et al., 2014.

The committee was not tasked with performing a systematic review of all the literature related to NETs. Fortunately, because of the widespread interest in NETs, the committee had access to several recent and comprehensive reviews including Fuss et al., 2018, Minx et al., 2018, and Nemet et al., 2018.

BOX 1.2
ASSESSING THE NEED FOR NETS

To complete its task, the committee assessed the urgency of developing new and/or improved NETs. Apart from two NETs with large co-benefits, NETs will only be deployed to reduce atmospheric CO_2. Thus, the coming economic and social demand for NETs can only be assessed in reference to a plan for climate mitigation. The committee assessed the need for NETs using the target from the Paris Agreement that warming be limited to substantially less than 2°C and ideally 1.5°C. And recently, the IPCC, 2018 concluded that limiting global warming to 1.5°C with limited or no overshoot will require the use of NETs by the middle of this century.

Any statement in this report about the *need* for an emissions reduction of a particular size should not be interpreted as a normative statement (a value judgment on what should be), but rather as a statement about action required *given a decision to meet the Paris agreement or to provide NETs to the international market by most nations, many corporations, and several U.S. states and local governments*. Nonetheless, the committee is acutely aware that the U.S. government has announced an intention to withdraw from the Paris Agreement.

It is useful to ask how different the report's conclusions would be without the constraint of the Paris agreement. The committee believes that its conclusions and recommendations are generally robust, simply because the economic rewards for success would be so large. This is due to the U.S. government's ongoing commitment to reduce climate change, as evidenced by the recently adopted 45Q rule[a] that provides a tax credit of \$50/t CO_2 for capture and storage, and the ongoing commitments to the Paris agreement by most nations, many corporations, and several U.S. states and governments.

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[a] https://www.law.cornell.edu/uscode/text/26/45Q.

NEGATIVE EMISSIONS TECHNOLOGIES

In response to item E of the Statement of Task, the committee focused on five major approaches (see Figure 1.6):

- Coastal blue carbon (Chapter 2)—Land-use and management practices that cause an increase in the carbon stored in living plants or sediments in mangroves, tidal marshlands, seagrass beds, and other tidal or salt-water wetlands. These approaches are sometimes called "blue carbon" even though they refer to coastal ecosystems instead of the open ocean.
- Terrestrial carbon removal and sequestration (Chapter 3)—Land-use and management practices within forests or agricultural lands that increase the total inventory of carbon in the terrestrial biosphere. These include the following:
    - Management methods on croplands or pastures, such as reduced tillage

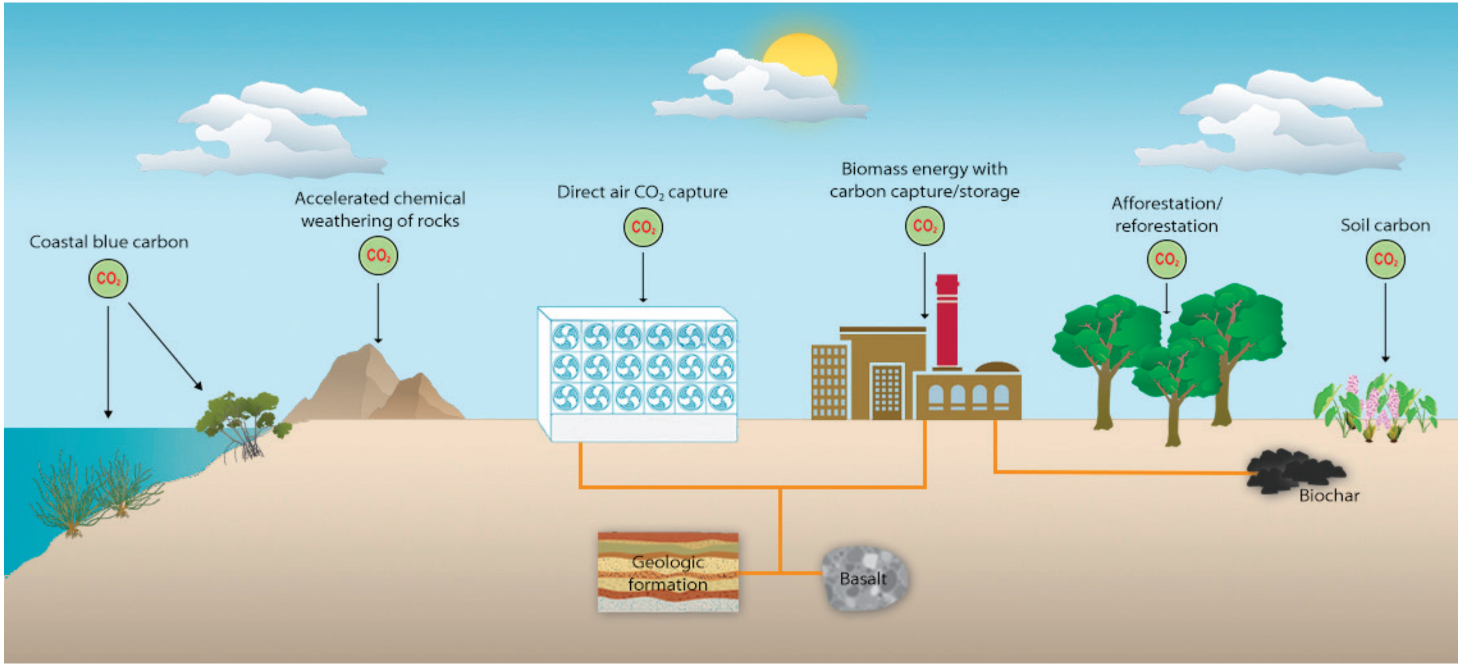

FIGURE 1.6 Negative emissions technologies considered in this report.

BOX 1.3
NATIONAL ACADEMIES STUDIES ON CARBON REMOVAL AND USE: DEVELOPING A RESEARCH AGENDA FOR CARBON DIOXIDE REMOVAL AND RELIABLE SEQUESTRATION & DEVELOPING A RESEARCH AGENDA FOR UTILIZATION OF GASEOUS CARBON WASTE STREAMS[a]

Recognizing the important role of CO_2 removal and sequestration technologies in meeting greenhouse gas reduction goals, the National Academies convened an ad hoc committee to evaluate the state of science and viability of technologies for removing CO_2 from the atmosphere. The resulting report, *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* (NRC, 2015b), recommended investments in research and development (R&D) for technologies that remove CO_2 from the atmosphere. Building on this report, the National Academies convened two committees, one to identify research needs for CO_2 removal from the atmosphere and sequestration, and one to study utilization of concentrated carbon waste gas streams. The Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration assessed the benefits, risks, and "sustainable scale potential" for atmospheric CO_2 removal and sequestration approaches and defined the essential components of an R&D program, including estimates of the program's cost and potential impact. The Committee on Developing a Research Agenda for Utilization of Gaseous Carbon Waste Streams developed a research agenda for conversion of concentrated waste gas streams of CO_2, methane, and biogas as a feedstock into commercially valuable products. That committee surveyed the current landscape of carbon utilization technologies and identified key factors and criteria associated with making these technologies commercially viable. Together, the two committees' reports provide an assessment of research needs and opportunities to remove and utilize gaseous carbon.

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[a] See http://dels.nas.edu/Study-In-Progress/Developing-Research-Agenda-Utilization/DELS-BCST-16-05.

BOX 1.4
STATEMENT OF TASK

A. Identify the most urgent unanswered scientific and technical questions needed to:
   i. assess the benefits, risks, and sustainable scale potential for carbon dioxide removal and sequestration approaches in the terrestrial and nearshore/coastal environment; and
   ii. increase the commercial viability of carbon dioxide removal and sequestration;
B. Define the essential components of a research and development program and specific tasks required to answer these questions;
C. Estimate the costs and potential impacts of such a research and development program to the extent possible in the timeframe of the study.
D. Recommend ways to implement such a research and development program.
E. The list of carbon dioxide removal approaches to be examined would include land management, accelerated weathering, bioenergy with capture, direct air capture, geologic sequestration, nearshore/coastal approaches, and other approaches deemed by the study committee to be of similar viability.

or the planting of cover crops that increase the total amount of undecomposed organic carbon in the soils ("agricultural soils").

  - Planting forest on lands that used to be forest, but were converted to another use ("reforestation"), or planting forest on lands that were originally grasslands or shrublands ("afforestation").
  - Management practices that increase the amount of carbon per unit land area on existing forest, such as accelerating regeneration after disturbance or lengthening harvest rotations ("forest management").

- Bioenergy with carbon capture and sequestration[4] (BECCS; Chapter 4)—Photosynthesis captures atmospheric CO_2 and energy from sunlight and stores both in plant tissues. BECCS combines the production of energy from plant biomass to produce electricity, liquid fuels and/or heat with capture and sequestration of any CO_2 produced when using the bioenergy and any remaining biomass carbon that is not contained in the liquid fuels. This report focuses on biomass combustion for power and thermochemical conversion to fuel because they have the highest carbon negative potential, as opposed to biological biomass conversion that is fundamentally limited due to the inability to break down lignin (up to 25 percent of all biomass).
- Direct air capture and sequestration (Chapter 5)—Chemical processes capture and concentrate CO_2 from ambient air so that it can be injected into a storage reservoir. In some incarnations, the captured CO_2 may be reused in products. Capture and reuse in short-lived products, such as chemical fuels, is not included in this report as a NET, because the carbon in the products would be returned quickly to the atmosphere. However, capture in long-lived products, such as many structural materials, is included, because the product itself is then the storage reservoir. Carbon capture and re-use is the subject of a separate National Academies study that is discussed in Box 1.3.
- Carbon mineralization (Chapter 6)—Accelerated "weathering," in which CO_2 from the atmosphere forms a chemical bond with a reactive mineral (particularly mantle peridotite, basaltic lava, and other reactive rocks). Carbon mineralization includes both at the surface (ex situ) where CO_2 in ambient air is mineralized on exposed rock and in the subsurface (in situ) where concentrated CO_2 streams captured through either BECCS or direct air capture are injected into ultramafic and basaltic rocks where it mineralizes in the pores.
- Geologic sequestration (Chapter 7)—Supercritical CO_2 is injected into a

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[4] BECCS includes both combustion-based methods that utilize biomass to generate electricity, with CO_2 being sequestered from the flue gas, and pyrolysis-based methods that use biomass to produce liquid biofuels and biochar, with the biochar represented the negative carbon potential.

geologic formation where it remains in the pore space of the rock for a long period of time. This is not a NET, but rather an option for the sequestration component of BECCS or direct air capture. It is treated by a separate chapter, to avoid repetition in the BECCS and direct air capture chapters.

The committee used the above list of NETs as an organizing framework for both information gathering and report development. Many of the elements on the list are well documented in an extensive literature and are relatively straightforward to describe to policymakers and the public. The collection includes NETs at very different stages of technological readiness, and so the recommended research program called for in item A of the Statement of Task spans the full range from basic scientific research to final pre-deployment studies. Given the relative nascency of coastal blue carbon, direct air capture, and carbon mineralization approaches in the literature, these approaches are described in much more technical and comprehensive detail in their respective chapters, with supplemental technical details for direct air capture and carbon mineralization included in Appendices D and E.

The committee's focus on sequestration in terrestrial and nearshore/coastal environments is not intended to undervalue the potential of technologies or practices for oceanic sequestration, but instead is a response to the Statement of Task. The oceans already contain 36,000 Gt C, mostly in the form of bicarbonate (equivalent to 132,000 Gt CO_2). Once the fossil fuel age is over, almost all of the anthropogenic CO_2 in the atmosphere will ultimately make its way into the oceans (centuries to millennia) and finally into carbonate minerals on the sea floor (tens of millennia). Promising technologies exist for oceanic sequestration, some with potentially limited environmental impact, and the capacity of the oceanic carbon reservoir is obviously enormous. Explored approaches include increased biomass production and ocean alkalization. This committee was not convened to cover the physical, chemical, and biological dimensions of oceanic options, or the complex international rules and negotiations that would permit oceanic disposal. Consideration of oceanic options would require a separate study. Near-shore/coastal is included with the terrestrial options, rather than with oceanic options, because the near-shore/coastal ecosystems assessed in this study store carbon in living plant tissues and undecomposed organic matter in soils/sediments, like terrestrial ecosystems, and unlike most oceanic options.

The exclusive focus of this report on NETs is also a reflection of the Statement of Task. Although the report addresses the relationship between NETs and decarbonized power (i.e., a direct air capture system powered by fossil fuel has a much higher cost/net CO_2 than a system powered by decarbonized power), it does not address critical mitigation options such as enhanced energy efficiency, renewable electricity, or reduced deforestation because they are not NETs. Their exclusion is in no way a statement about priorities. The committee is acutely aware that the possibility of large negative emissions in the future might result in a moral hazard, by reducing the will to cut emissions in the near term (Anderson and Peters, 2016). Emissions reductions are vital to address the climate problem. However, policymakers benefit from consideration of the broadest possible portfolio of technologies to find the most inexpensive and least disruptive solution, including those with positive, near-zero, and negative emissions. In addition, a broad portfolio of technologies (including multiple NETs) offers increased resiliency to managing the risks of surprises arising from nature and mitigation actions. Furthermore, the possibility of irreversible consequences of temporary warming is another reason to quickly develop NETs so that they can more quickly reduce net anthropogenic emissions.

Framework for Assessing Individual NETs

The Statement of Task specifies two main purposes of this report: (1) to assess each NET and identify the most critical unanswered questions about benefits, costs, potential scale, and risks, and the most important barriers to commercial viability and (2) to propose an R&D program, with estimated costs and implementation (including monitoring and verification, institutional structures, and research management). NETs span a range of technological readiness, and therefore the assessments and recommendations for the different options are highly heterogeneous. Nonetheless, Chapters 2-7 share a few elements. Each chapter focuses on two scales, the United States and the globe, and on research designed to funded by the United States. Each defines the approach and describes the technology, impact potential for CO_2 removal and sequestration, cost per ton of CO_2, barriers to cost reductions, secondary impacts (including co-benefits), and requirements and costs of the proposed research agenda. The committee developed these estimates, research agenda, and costs based on its expert judgment after reviewing the relevant literature and hearing from experts at committee workshops and webinars.

Impact Potential. Upper-bound estimates of the potential rate and capacity for carbon capture and sequestration are constrained primarily by hard barriers such as available pore space in geologic reservoirs or available land area. Practically achievable rates and capacities reflect the committee's judgment about levels of deployment that could be achieved given economic, environmental, societal, and other barriers to scale-up. Thus, the practically achievable estimates required the uncertain integration of a large number of option-specific factors, many of which are themselves uncertain. Each chapter attempts to explain clearly how these estimates were obtained. In general, the committee restricted its investigation to methods that have a practically achievable potential of at least 1 Gt/y CO_2e globally. In addition, these estimates include considerations of all the processes that might cause CO_2 emissions, from carbon capture to ultimate sequestration, and possible leakage of CO_2 back to the atmosphere after sequestration. For example, the carbon implications of the input energy requirement for a technology such as direct air capture is needed.

A particularly challenging problem associated with carbon flux is permanence, that is, that leakage from a CO_2 storage reservoir may occur a century or more after initial sequestration. How long does sequestered carbon need to remain below ground or locked in the organic matter in an ecosystem? Because CO_2 has an average residence time in the atmosphere of more than a century, and because dissolved CO_2 acidifies the oceans and persists for millennia before being deposited in carbonate sediments, a typical answer is that carbon needs to be stored, on average, for millennia.

In contrast, it is difficult to imagine any set of policies that would guarantee 1,000-year carbon storage in an ecosystem, as reflected in current markets for forestry offsets that stipulate storage for the next 20-100 years (Hamrick and Gallant, 2017). Fortunately, economic calculations typically produce more achievable requirements than a purely scientific analysis, because economic discounting reduces the present cost of any re-emission that occurs far in the future. However, in the absence of high-capacity NETs, economic calculations still must include the costs of climate change that cannot be mitigated if caused by CO_2 re-emitted after the end of the fossil era.

However, NETs provide the possibility of capturing and re-sequestering CO_2 as it is lost from storage reservoirs. If the price of capture and sequestration is P \$/t CO_2, the economic discount rate is r, escape from reservoirs occurs at a constant rate per unit of carbon stored, and the average residence time of CO_2 in a reservoir is T, then the additional present cost of recapturing and re-sequestering escaped CO_2 forever is $\int_0^\infty \frac{P}{T} e^{-rt} dt = \frac{P}{Tr}$. If Tr>1, then the expense required to recapture and re-sequester escaped CO_2 in perpetuity has small present value relative to the cost of initial capture and sequestration. For example, if the discount rate is 5 percent and T is 100 years, then the present cost of effective permanence adds 20 percent to P. Moreover, continued monitoring would reduce costs further, because re-sequestration would avoid sites with a poor record of containment.

Each chapter also estimates costs to establish NET and/or sequestration projects and for annual operation in two cases: prior to scale-up (i.e., today's cost for almost all options) and once a method or technology is implemented at scale. The committee also examined barriers to scale-up other than current costs, and the potential for future cost reductions. The estimated costs are specifically not reductions in the size of the economy caused by public investment in carbon removal and sequestration, like those produced by general equilibrium models in economics.

Secondary Impacts. Because NETs could make a substantial contribution to solving the climate problem only if they can create billions of tons of negative CO_2 emissions, collateral benefits and costs are inevitable, and potentially substantial. The committee assessed:

(1) environmental impacts including emissions of non-CO_2 greenhouse gases, biophysical effects of land cover change on climate and river runoff (primarily from changes in albedo and evapotranspiration), increased extinction from habitat loss, and changes in nitrogen runoff;
(2) potential co-benefits including electricity generation or biofuel production for BECCS, new industries, and improved agricultural productivity, soil nitrogen retention, and soil water holding capacity for cropland soil CO_2 removal and sequestration; and
(3) societal impacts from changes in the supply of food, fiber, water, and other materials and public acceptance of scale-up.

Research Agendas. Chapters 2-7 propose and justify research programs for each NET as well as considerations for implementation of the research programs, including assessing constraints for the development and deployment of NETs imposed by the legal system, infrastructure requirements, public perception, and system-integration requirements. The recommended research agenda is presented in terms of (1) basic science questions (knowledge gaps), (2) development (technology issues), (3) demonstration (engineering and economics), and (4) deployment (scale-up barriers, economics, and governance). Each chapter contains estimated costs of the research agenda and outlines implementation of the research agenda—monitoring and verification, institutional structures, and research management.

Many of the research agenda budgets are intended to be staggered over a period of several years. Therefore, the simple addition of budget line items does not provide an accurate picture of total annual budgets for any given component or task. Moreover, as projects are scaled up from bench, to pilot, to demonstration-scale prototypes, they should pass through a comprehensive review (stage-gate) before funding is allocated for scale-up to the next prototype size. The coordination between these stage-gates, prototype scales, technology readiness levels, and research phases is shown graphically in Figure 1.7. This approach is intended to reduce technology and financial risk. As such, it is entirely possible that no program funding is needed for pilot and

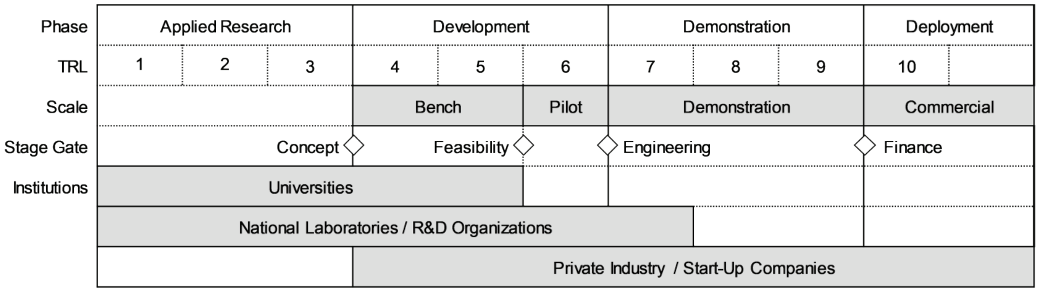

FIGURE 1.7 Illustration of coordination between research phases, technology readiness level (TRL), prototype scale, stage-gates, and institutions.

demonstration-scale prototypes, because there may be no eligible projects (i.e., no projects able to achieve the program metrics and thus not advance to the next stage of development).

Synthesis

The research agendas proposed in Chapters 2-7 are combined in Chapter 8 into an integrated research proposal and a single list of research priorities. In addition, Chapter 8 examines national- and global-scale CO_2 removal and sequestration holistically, rather than one option at a time, to understand better the interactions among NETs. Because the scale of deployment is potentially so large, interactions are inevitable, including competition for the same land, water, and materials and synergistic environmental and societal impacts.

CHAPTER TWO

Coastal Blue Carbon

INTRODUCTION

Overview of Coastal Blue Carbon—Definition and Motivation

Coastal carbon sequestration, in this report, refers to carbon dioxide (CO_2) removal from the atmosphere in conjunction with plant growth and the accumulation and burial of plant organic carbon (OC) residue in the soil of tidal wetland and seagrass ecosystems. Tidal wetlands, including salt marshes and mangroves, thrive in soft-sediment, shallow regions of estuaries between high and mean sea level, while seagrasses inhabit adjacent soft-sediment estuarine bottoms with adequate light penetration. Macroalgal systems such as kelp forests, while extremely productive, do not have root systems and soils to accumulate carbon (Howard et al., 2017). Little is known about the fate of macroalgal OC, a portion of which could potentially be sequestered by other means when exported from the macroalgal bed (Krause-Jensen et al., 2018). Further understanding of macroalgal transport processes or other farming approaches that could permanently remove CO_2 from the atmosphere is needed to assess the potential for globally significant levels of CO_2 sequestration. Given the state of research on this topic, which is summarized in Appendix C, the CO_2 removal capacity of macroalgal storage is not a focus of this chapter. Other ocean-based negative emissions technologies (NETs), such as sequestration in microbial or planktonic biomass (Zhang et al., 2017b) and ocean alkalization (Rau et al., 2013; Renforth and Henderson, 2017), may be conducted in the coastal environment but are essentially open ocean approaches. They remove carbon through very different mechanisms from coastal wetlands, which bear closer similarity to terrestrial-based NETs. As described in Chapter 1, these approaches are not included in this report and warrant further investigation because of the potentially large role that ocean sinks can play in CO_2 removal.

Tidal wetlands and seagrasses are among the most productive regions on Earth, sequestering CO_2 at a rate of 7.98 t/(ha y) CO_2 for tidal wetlands and 1.58 t/(ha y) CO_2 for seagrass meadows (EPA, 2017; IPCC, 2014a). Scaled to their current global areal extent, they are an important component of the global carbon cycle. Tidal wetlands grew to their current areal extent only in the past 4,000-6,000 years, once the rate of sea-level rise (SLR) declined to less than 2 millimeters per year. The OC that has accumulated over this time is deep and vast, ranging from 2 to 25 Gt C (best-estimate of 7 Gt C; Bauer et al., 2013; Donato et al., 2011; Fourqurean et al., 2012; Pendleton et al., 2012; Regnier et al., 2013). The recent State of the Carbon Cycle Report (SOCCR-2) estimates that tidal marsh wetland soils and estuarine sediments of North America store roughly 1.323 Gt C as the top 1 m of soil and sediment. However, coastal soil profiles are known to reach greater depths, and thus carbon storage is higher than this estimate (Sanderman et al., 2018). Variation in soil and sediment depths have become an increasingly recognized source of uncertainty in tidal wetland coastal carbon stocks, in addition to other sources of uncertainty (Holmquist et al., 2018). Although seagrasses have lower OC burial rates than tidal wetlands per unit area, they potentially cover a much larger area and thus could have higher total carbon rates and sequestration capacity. However, substantial difficulties in large-scale estimation persist because there is large variability in measurements of seagrass OC stocks and burial rates. The mapping of seagrass areas in U.S. water is also limited; less than 60 percent of meadows are mapped, and existing maps have varying degrees of accuracy because of difficulties in remote sensing of underwater habitat (Oreska et al., 2018).

Annual rates of coastal carbon sequestration are also high. Globally, the total carbon sequestration rates are estimated at 31-34 Mt/y C for mangrove, 5-87 Mt/y C for salt marshes, and 48-112 Mt/y C for seagrass beds, or 226 ± 39 g/(m^2 y)C for mangrove, 218 ± 24 g/(m^2 y)C for salt marshes, 138 ± 38 g/(m^2 y)C for seagrasses, summing up to a global annual rate of 0.84 Gt/y CO_2 (Mcleod et al., 2011). According to the *U.S. Inventory of Greenhouse Gas Emissions and Sinks*, U.S. tidal wetlands (marshes and mangroves) sequester more than12 Mt/y CO_2 and a net of about 8 Mt/y CO_2e when both CO_2 and CH_4 (methane) fluxes are considered (EPA, 2017). The CH_4 fluxes introduce significant uncertainty in large-scale estimates because of difficulties with detecting salinity boundaries that determine CH_4 flux rates (Poffenbarger et al., 2011). For North America, soil OC accretion rate (sediment burial) was 5 ± 2 Mt/y for tidal marshes, 2 ± 1 Mt/y for mangroves and 1 ± 1 Mt/y for seagrass meadows (30 Mt CO_2 in total; SOCCR-2). The estimate produced by the U.S. Environmental Protection Agency (EPA) was only for the continental United States and included fewer wetland areas and tidal wetland types than the North American SOCCR-2 report. The EPA report also did not include seagrass meadows. Tidal wetlands, particularly mangroves, also sequester CO_2 in aboveground biomass via long-term storage in wood and woody stems. Although this contributes to negative CO_2 emissions, this CO_2 removal flux is omitted from estimates presented in this report because most recent U.S. estimates focus on soils only as it is the proportionally larger sink for tidal marsh ecosystems that represent the largest area of coastal carbon ecosystems in the United States.

The motivation for including coastal blue carbon as a potential NET is the potential to more than double the current rate of CO_2 removal through several approaches that restore and create coastal wetlands. Further, there is concern that the current rate of sequestration will drop substantially because of expected changes in factors that contribute to sequestration, especially those that affect the current areal extent and carbon burial rate per unit area. Sequestration is vulnerable to impacts from climate change, including increasing rates of SLR (Figure 2.1) and rising temperatures, and human activities in the coastal zone. Although conversion of U.S. coastal wetlands has slowed, it is estimated that global drainage and excavation of mangrove, tidal marsh, and seagrass soils release 450 million tons of CO_2 annually (range 150-1,005 Mt/y CO_2; Pendleton et al., 2012). In addition, declining sediment supplies and groundwater/oil and gas extraction pose indirect threats to wetlands (Megonigal et al., 2016). Reversing historic loss and degradation through restoration, incorporating wetland creation into coastal adaptation projects, and managing wetland area and carbon

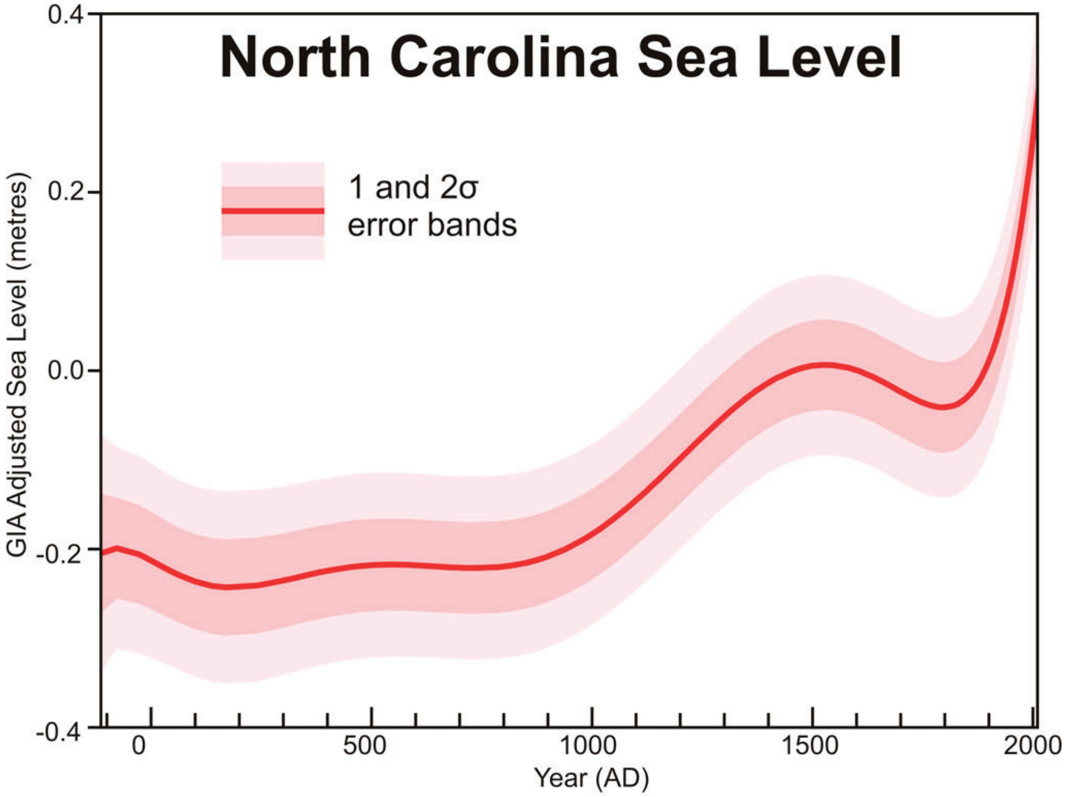

FIGURE 2.1 Relative sea level over the last 2000 years, reconstructed using analysis of microfossils in sediment from salt marshes in North Carolina and recent acceleration. SOURCE: Kemp et al., 2011.

accumulation rates provide an opportunity for increased carbon removal and storage through the 21st century.

Coastal wetlands and seagrasses are already the targets of restoration and management for the broad range of ecosystem services they provide beyond CO_2 removal, including coastal storm protection and wave attenuation, water quality improvement, wildlife habitat, and support of fisheries (Alongi, 2011; Barbier et al., 2011; Lee et al., 2014; Nagelkerken et al., 2008; Zhang et al., 2012). These activities and investments, which are not included in this report as NET costs, can be leveraged to provide CO_2 removal advantages at marginal costs.

COASTAL BLUE CARBON PROCESSES

Coastal carbon sequestration is calculated for each ecosystem as the product of its areal extent (horizontal dimension) and its vertical OC accumulation rate (vertical dimension) (Hopkinson et al., 2012). During the past 4,000-6,000 years, the rate of SLR slowed enough to allow tidal wetlands to maintain or expand their areal extent and their vertical elevation relative to SLR (Figure 2.2). The survival of existing tidal wetlands requires that vertical elevation gains at least match the rate of SLR. Tidal wetlands form with salt-tolerant plants in soft-sediment intertidal regions above mean sea level (MSL). Once established, the elevation of wetlands increases relative to sea level (SL) through the accretion of particles trapped by wetland vegetation from tidal waters (watershed, oceanic, or local sources) and the accumulation of undecomposed wetland plant organic matter. The rate of accretion and carbon burial varies hyperbolically with flooding frequency and depth and thus the rate of SLR (see Figure 2.3; Morris, 2016). With adequate sediment supply relative to the rate of SLR and local subsidence (or rise), sedimentation leads to the shallowing of estuaries. Tidal wetlands prograde into formerly open water regions, once depths reach MSL, thereby increasing their horizontal extent. Tidal wetlands will also expand horizontally through transgression when rising seas flood adjacent upland areas and wetland plants invade.

In seagrass meadows, lateral expansion occurs through asexual clonal growth. Seagrasses also disperse seeds to colonize new areas. Within seagrass meadows, OC is accreted vertically when wave attenuation from the plant canopy causes sediment to settle from the water column and bury plant detritus as well as allochthonous carbon. About one-half of the carbon buried in seagrass beds is produced by non-seagrass sources (Oreska et al., 2018). Carbon burial varies spatially within a meadow; wave attenuation is more effective in inner parts of the meadow, with greater erosion occurring at the edges (Oreska et al., 2017). Seagrass bed productivity is controlled by

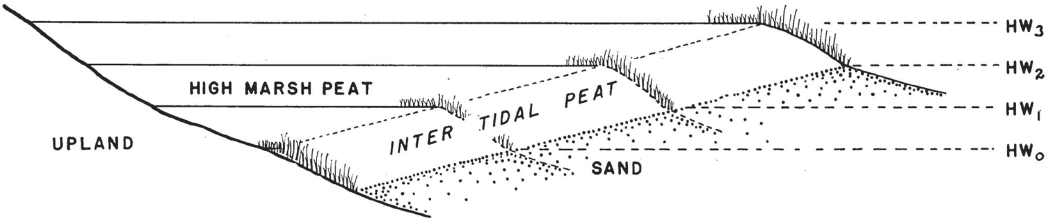

FIGURE 2.2 Redfield model of tidal wetland development over the past several thousand years as a result of bay infilling and marsh progradation, sediment and OC burial and elevation gain, and flooding of uplands as sea level rises and wetlands transgress upland habitats. Example from Barnstable Harbor, Massachusetts. SOURCE: Redfield, 1972.

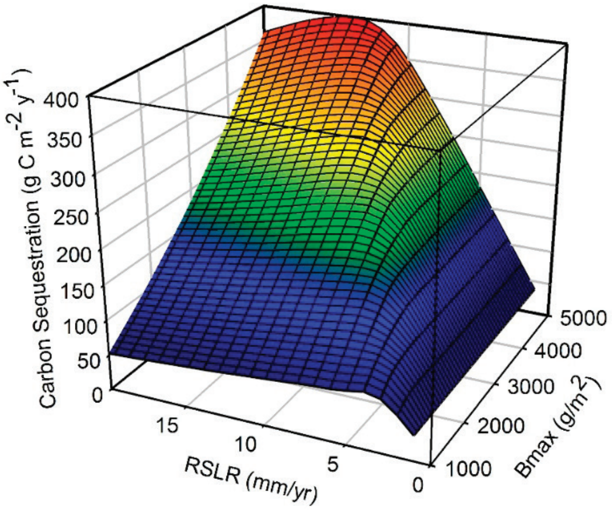

FIGURE 2.3 Carbon sequestration is a function of the rate of relative sea level rise (RSLR) and maximum marsh biomass (B_{max}) as depicted by simulations of the Marsh Equilibrium Model. SOURCE: James Morris, presentation to committee.

different factors including nutrient and light availability (Apostolaki et al., 2011; Hendriks et al., 2017). Light availability is controlled by a variety of factors including water depth and turbidity. Turbidity is related to local geomorphic drivers as well as eutrophication (which controls phytoplankton density) and growth of epiphytes on leaves (a factor contributing to reduced photosynthesis of submerged macrophytes).

Critical to coastal carbon sequestration is the rate of vertical elevation gain and specifically the relative contribution of undecomposed plant OC to mineral sediments. In tidal wetlands, most of the OC accumulating is that produced in situ (autochthonous), while in seagrass meadows trapping of OC from external sources (allochthonous) can be important as well. The fate of wetland plant biomass production varies tremendously from system to system depending on the rates of net primary production (NPP), respiration of microbes and larger animals living on and in tidal wetlands (Re) (i.e., decomposition and consumption of OC), and the tidal export of undecomposed plant material (Hopkinson, 1988), which is mostly above-ground plant material. The balance between NPP, Re, and export is the organic matter that is buried and preserved. The continued surface deposition acts to increase over time the depth of OC within the sediment, where conditions reduce organic matter decomposition, thus preserving it for longer and longer periods of time (Redfield, 1972).

The dynamic exchange and export of OC to adjacent systems is a unique characteristic of tidal and estuarine systems compared with terrestrial ecosystems. Carbon that is exported laterally may exit the coastal ocean through CO_2 outgassing or dissolved OC and particle carbon export to the open ocean, with carbon import across these interfaces also possible. The balance of these processes results in annual OC storage at higher rates than long-term OC sequestration (Breithaupt et al., 2012). To simplify the Committee’s treatment of negative carbon emissions in this study, the focus in this chapter is on long-term (50-100 years), buried soil carbon.

COASTAL BLUE CARBON IN THE FUTURE—THE IMPACTS OF CHANGING ECOSYSTEM DRIVERS

The baseline carbon sequestration capacity for coastal wetlands and seagrass meadows is the predicted changes in areal extent and OC burial rates of these ecosystems in the absence of human intervention. Without any human intervention, this baseline is possibly decreasing over time, as compared with the current burial rate, under the stress of climate change and human activity. It is upon this expected baseline that CO_2 removal approaches to increase future CO_2 removal trajectories can be evaluated. Extrapolating past and current rates of CO_2 removal to predict future rates of

CO_2 removal likely will not provide accurate estimates, because drivers are changing rapidly in many coastal areas. The heart of a research agenda is to fill knowledge gaps on the response to these changing drivers, and to constrain uncertainties in coastal blue carbon to better predict and manage future trajectories and accelerate new opportunities for CO_2 removal.

The drivers of concern are those most likely to change as a result of climate change or other anthropogenic impacts over the next hundred years, including

- relative SLR (which affects extent, depth, and duration of tidal flooding),
- sediment availability (from watershed inputs, tidal flooding and/or storms),
- temperature (and growing season length),
- light availability,
- salinity (related to river flow, local climate, and sea level),
- inorganic nitrogen and phosphorous availability and enrichment, and
- development of wetland area or uplands adjacent to wetlands.

Partially or fully driven by the above abiotic factors, biotic factors include:

- plant productivity and species composition,
- plant migration rates, and
- organic matter decomposition rates.

Expansion of tidal wetlands into open water areas of estuaries has slowed and, in some places, has reversed during the past 100 years or so, primarily because of decreased sediment input due to watershed management activities compounded by increased rates of relative SLR. Increased rates of SLR have also increased transgression (the expansion of wetlands into terrestrial uplands). SLR interacts with anthropogenic stressors and can result in accelerated erosion and subsidence in certain conditions. Several models have been developed to provide a predictive understanding of both the areal extent and OC burial components of tidal wetlands (French et al., 2008; Kirwan et al., 2010, 2016b; Morris et al., 2002; Morris, 2016; Mudd, 2011). Models show that a simple bell-shaped relationship between elevation and productivity characterizes tidal biomass production and a linear elevation–decomposition relationship characterizes belowground organic carbon degradation (Figure 2.3). Current models suggest the existence of a threshold level of sea level where the vertical elevation and lateral migration of tidal wetlands may not keep pace with the water level, resulting in wetland drowning and a sudden decrease in OC burial (Figure 2.4). In addition to driving the vertical response, SLR can drive the migration of tidal wetlands inland (transgression) and either into open water (progradation) or into interior wetlands (redeposition of eroded carbon) (Figure 2.5). Without adequate sediment supply to maintain

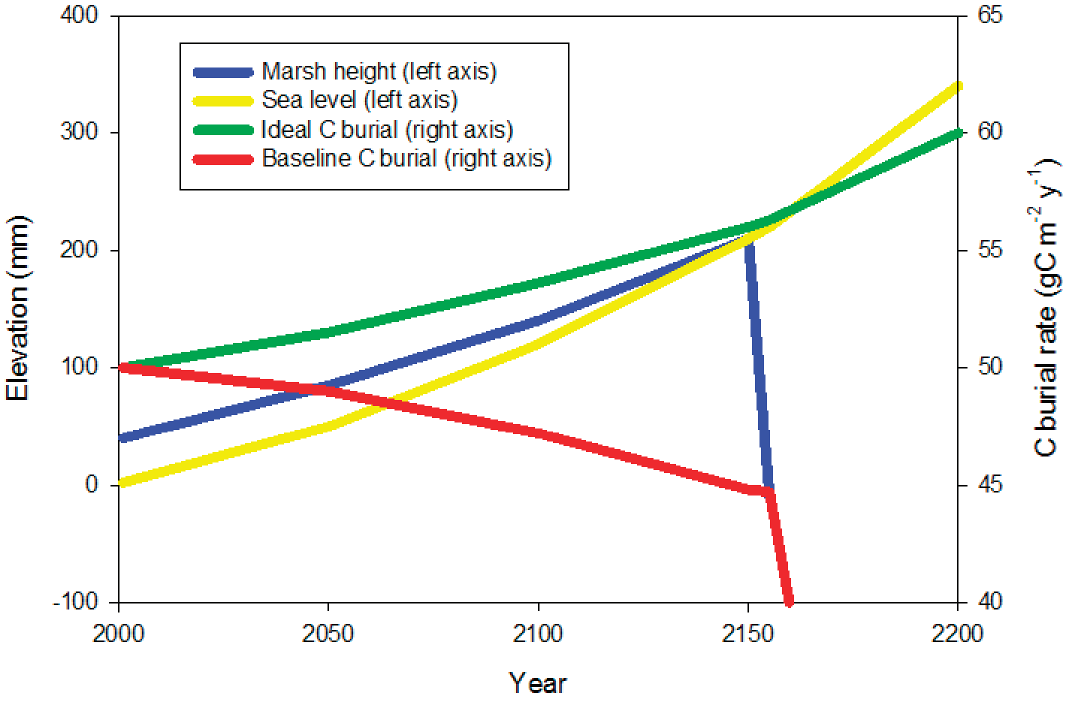

FIGURE 2.4 Hypothetical projection of marsh height (blue), sea level (yellow), ideal carbon burial rates (green), and baseline carbon burial rates without human intervention (red). NOTES: Impact of relative rate of SLR exceeds the growth in elevation of tidal wetlands until the year 2150 (in this example) when the marsh collapses. Without human intervention, the projected baseline of carbon burial rates decreases from the current 50 g/(m^2 y) C to 0 in year 2150 when the marsh collapses.

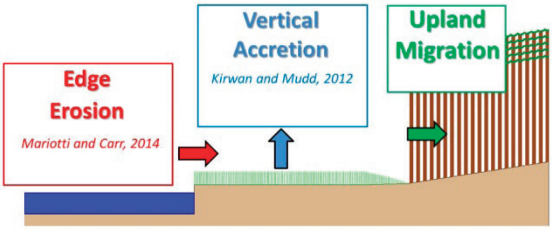

FIGURE 2.5 OC carbon balance through upland migration (transgression), shoreline erosion (or progradation), and vertical accretion, which includes OC burial. SLR and sediment availability are two of the most important factors controlling the OC balance. SOURCE: Modified from Kirwan et al., 2016a.

a critical depth of tidal flats adjacent to tidal wetlands, erosion of the edge of existing wetlands can result in decreased areal extent (Mariotti and Fagherazzi, 2010, 2013; Mariotti and Carr, 2014). Thus, the future expanse of tidal wetlands will reflect the balance between positive or negative progradation/erosion and upland transgression.

Despite the value of these predictive models, knowledge gaps remain that affect the ability to predict future CO_2 removal capacity. One key gap is the fate of eroded OC. When a wetland erodes or is drowned, the fate (i.e., whether it will decompose and contribute to carbon emissions, be deposited and buried long term, or be redeposited on the marsh platform) depends on geomorphological processes controlling erosion, deposition, and resuspension (Hopkinson et al., 2018). Better understanding of what could happen to eroded carbon will require better understanding of OC preservation and its refractory nature and transport depositional fate. In addition, although there is apparent agreement between current models of tidal wetland OC burial and selected field observations, reliance on old paradigms of OC preservation in soils (Lehmann and Kleber, 2015; Schmidt et al., 2011) and on microcosm results as evidence for a hyperbolic response of tidal wetland platform vegetation to flooding do not lend confidence to predictions of marsh survival and OC burial if sea level increases by 1-2 m by century end (Morris, 2016). Regional and local drivers and recent changes, including human impacts, can limit the broad predictive ability of these models. Nevertheless, experimental manipulations coupled with hierarchical approaches to scaling, and better integration of field-validated remote sensing, have greatly improved integration of plot-based drivers of OC accumulation rates and landscape-scale estimation of coastal wetland CO_2 removal (Byrd et al., 2018; EPA, 2017; Holmquist et al., 2018).

The future CO_2 removal capacity of tidal wetlands depends on their ability to transgress into upland areas as SLR increases. “Coastal squeeze” and vegetation shifts may reduce the lateral space for wetland transgression into uplands. Coastal squeeze occurs when there is no more lateral space for upland migration (DOE, 2017a; Doody, 2004). The decline in available lateral space results from upland barriers, when uplands are occupied by other land uses (e.g., agriculture, urban lands) or when the slope does not support the migration of wetlands into upland areas (Doody, 2004). Prediction of the trajectories of available lands is another key knowledge gap, including what factors may reduce barriers to wetland transgression into uplands that are occupied by other land uses. Vegetation shifts associated with wetland transgression and change in carbon uptake capacity, as in shifts to woody species or loss of vegetated wetland from inland subsidence due to marsh dieback, can result in overall changes in carbon burial rates.

Warming of the air and sea water will impact the coastal carbon cycling and sequestration driven by complex interaction of plants, microbes, and physical processes (Megonigal et al., 2016). Both primary production and OC decomposition could increase with warming. While theory and mesocosm studies of estuarine water show that warming will differentially increase Re relative to NPP, which would thus decrease net ecosystem productivity (NEP) and the potential OC available for either burial or export, data are insufficient to extrapolate these results to tidal wetland and seagrass ecosystems (Yvon-Durocher et al., 2010). Warming could also drive the displacement of salt marsh by mangrove (Megonigal et al., 2016). The final carbon burial rate is determined by the rate and sensitivity of these processes to warming.

APPROACHES FOR COASTAL BLUE CARBON

The overall goal for a research agenda on coastal blue carbon is to be able to quantitatively evaluate the enhanced OC burial for a variety of management and engineering approaches under a changing suite of social barriers, human activities, and climate scenarios. These approaches build on our current understanding of the baseline of annual carbon burial rates and estimation of incremental carbon burial induced from these projects. The knowledge gaps for each of these approaches relate to both research and technology. The committee focuses on five approaches by which coastal blue carbon can be accelerated through 2060 and potentially for the remainder of the century. They vary in terms of potential cost, degree of human intervention required, technological readiness, and social barriers (likelihood of enactment).

1. Actively manage coastal wetlands and seagrass meadows to increase CO_2 removal against the decreasing baseline of carbon burial rates.
2. Restore coastal wetlands and seagrass meadows where they have been degraded or lost.
3. Convert hardened and eroding shorelines to natural shorelines consisting of wetland area as part of coastal adaptation.
4. Manage wetland transgression into uplands with change in SLR and human drivers/impacts.
5. Increase the carbon storage capacity of coastal wetlands and shorelines by augmentation with carbon-rich materials.

Active Ecosystem Management

As a result of increasing rates of SLR and human disturbance, the baseline carbon burial rate is declining over time (Figure 2.4), meaning the current capacity of natural negative emissions in coastal wetlands is shrinking. With active management, this trend could be reversed and the carbon burial rate could become equal to the current rate or increase over time. The field has reasonable estimates of OC burial in coastal macrophyte systems in the United States, albeit there are large uncertainties in current areal extent of seagrasses and medium confidence in their appropriate OC burial rates.

Key to maintaining existing areas of natural tidal wetlands and seagrass meadows is management practices to reduce the impacts of human drivers that cause coastal change. As described earlier, progress has been made in developing models to predict the future areal extent and OC burial rate for extant wetlands of the United States. Some of the largest uncertainties are the (1) interplay between sediment availability and OC accumulation, (2) effects of climate drivers and SLR on NEP and OC burial, (3) factors controlling edge erosion and the importance of released sediment on wetland platform survival, and (4) effects of other human activities, such as pollutant runoff, on NEP and OC burial. A Habitat Evolution Model that incorporated future SLR scenarios applied to the Tampa Bay Estuary indicated that, if managed, coastal habitats would remove about 74 Mt CO_2 from the atmosphere by 2100 (ESA, 2016). That model can be used to prioritize coastal wetland areas for active management.

Given the projected decline in the baseline of carbon burial, any management practices and projects that can reverse the trend is a coastal NET. For example, enhancing coastal nitrogen management by building sewage treatment systems could significantly reduce nitrogen leaching to salt marshes, enhance rooting depth and marsh productivity (Deegan et al., 2012). Sediments are also required to maintain elevation of tidal flats proximal to wetlands to prevent shoreline erosion (Bilkovic et al., 2017; Fagherazzi et al., 2012). Edge erosion may be controlled by either direct (e.g., dredging) or indirect (e.g., river diversions or removal of dams on rivers) addition of sediments. It can also be controlled directly by living shorelines or breakwaters immediately adjacent to wetland shorelines. The potential problem with preventing shoreline erosion via breakwaters is that it prevents the liberation of sediments internal to the estuarine system, which may be a critical source of sediment contributing to elevation gain of wetlands interior to their edge. Management strategies to conserve carbon at the edge of eroding shorelines or creating breakwaters that protect the CO_2 sequestration of inland coastal marshes before barrier islands degrade could maintain the negative CO_2 emissions achieved by these coastal wetlands (Bilkovic et al., 2017). Some states are protecting shorelines from erosion as an active management effort with associated policy and a regulatory framework (Bridges et al., 2015). Further, protecting inland coastal marshes not only sustains areas for OC burial but also protects significant stores of peat. Initial saltwater intrusion may influence CH_4 emissions (Neubauer et al., 2013), while old peat deposits may be vulnerable to decomposition upon salinization (Wilson et al., 2018). Breakwater-type living shoreline projects can slow edge erosion, but their contribution to the sediment needed for platform elevation gain is uncertain, because edge erosion may be an important contributor of sediment to maintain elevation of the remaining marsh platform. For example, at the Plum Island Ecosystems LTER, marsh erosion liberates sufficient sediment to meet almost 30 percent of the annual rate of sediment accumulation, with rivers only contributing 9 percent (Hopkinson et al. 2018).

Restoration of Lost or Degraded Coastal Wetlands and Wetland Creation

Wetlands are drained, excavated, and tidally-restricted as a result of human activities that reduce their area or their capacity to sequester CO_2 and confer other ecosystem services (Kroeger et al., 2017a). The goal of restoration is to return or improve wetland functions and provision of ecosystem services. OC sequestration accompanies ongoing restoration activities (Kroeger et al., 2017a), but often is not the primary or even secondary objective. However, reversing the effects of anthropogenic activities on coastal wetlands to both reduce the greenhouse gas (GHG) burden on the atmosphere and reinitiate processes that promote CO_2 removal has been taken up as part of national and international policy actions—for example, recent International Governmental Panel on Climate Change GHG Inventory Guidance (IPCC, 2014a) and a new component of EPA's National Greenhouse Gas Inventory (EPA, 2017)]. Tidal marsh restoration sites in the Snohomish Estuary have measured annual accumulation rates between 0.9 t/(ha y) C to 3.52 t/(ha y) C (3.3 t CO_2 to 12.9 t CO_2), depending on characteristics of the sites including project age and elevation (Crooks et al., 2014). Restoration sites in the Tampa Bay Estuary are estimated to have accumulated 217,000 t CO_2e[1] between 2006 and 2016 (ESA, 2016).

While restoration of tidal wetlands and seagrass meadows is occurring, the potential to increase the areas for restoration is significant (EPA, 2017). In the United States, approximately 1.3 million hectares (ha) of tidal wetlands and seagrasses have been converted to other land uses or otherwise lost and currently potentially available for restoration. Notably, the different land uses for these former coastal wetlands may pose significant barriers to their restoration. These land uses within the coastal boundary (upper limit mean higher high water [MHHW]) are characterized by the National Oceanic and Atmospheric Administration's (NOAA's) Coastal Change Analysis Program

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[1] For any concentration and type of greenhouse gas (e.g. methane, perfluorocarbons, and nitrous oxide) CO_2e signifies the concentration of CO_2 which would have the same amount of radiative forcing.

(C-CAP) as developed (low to medium-high intensity); cultivated (including pasture/hay and grassland), including some portion that are tidally restricted (Kroeger et al., 2017a); and open water/unconsolidated shore (and possibly older eroded areas) because of erosion of tidal wetlands or loss of seagrass meadows (Waycott et al., 2009).

Within developed and cultivated lands in the coastal zone, restoration of hydrology, either through reversing drainage or removing tidal restrictions, is likely the most important activity to restore wetlands. Restoring saltwater flow to a tidally restricted wetland allows for both a reduction in methane emissions and a reconnection to the SLR processes that promote soil accumulation (Kroeger et al., 2017b). In submerged areas where elevation must be increased, two sediment management activities can be applied: (1) direct addition to the marsh surface (e.g., through thin layer deposition) and (2) indirect addition to the estuary and then tidal current conveyance to the wetland surface (e.g., river diversions and dam removal along rivers). OC burial can restart once intertidal elevations are reached and wetland vegetation is established (Osland et al., 2014). For example, reversing coastal wetland loss to subsidence and SLR is the primary focus of the Louisiana Master Plan (CPRA, 2017). Dredged material has proven to be a valuable sediment source for wetland creation—and hence raising sequestration above a baseline. Approximately 194 million cubic yards of sediment are dredged annually from the nation's navigable waters (USACE, 2015). Mississippi River diversions are of a smaller scale and may be more influential in reversing wetland loss. However, significant uncertainty remains as to whether application of these approaches in all subsided or eroded coastal wetlands will achieve similar results given the interacting effects of other drivers of coastal change.

Only a fraction of coastal water has been surveyed for seagrass. Globally, the seagrass meadow is estimated to cover 30-60 million ha (Duarte et al., 2005; Fourqurean et al., 2012; Kennedy et al., 2010; Mcleod et al., 2011). Based on current extent and fraction of reported loss, the current area of U.S. seagrass meadows is estimated at 0.6 million ha (Waycott et al., 2009). For seagrass meadows, watershed management to improve water quality and clarity, control of sediment loads, and resuspension and replanting of degraded seagrass cover are well proven technologies to increase areal extent, productivity, and OC burial.

Although not widely applied in the United States, there has been a strong push to develop carbon markets for wetlands, particularly tidal wetlands. Despite the absence of a market, a methodology for crediting tidal wetland and seagrass restoration with carbon sequestration has been developed (Verified Carbon Standard VM0033).

Conversion of Hardened and Eroding Shorelines to Natural Shorelines

The conversion of hardened and eroding shorelines to natural and nature-based shorelines that can keep pace with SLR is a growing environmental risk reduction strategy (van Wesenbeeck et al., 2014). This strategy also serves as an effective approach to CO_2 removal when projects enhance wetland area or performance (Bilkovic and Mitchell, 2017; Bridges et al., 2015; Davis et al., 2015; Saleh and Weinstein, 2016). Risks from flooding and storm surge are increasing and will impact coastal inhabitants in the United States and globally. Flooding of upland areas due to SLR is expected to place between 2.2 and 13.1 million people at risk, depending on SLR and population projections (Hauer et al., 2016). Because the estimated cost for relocation is $1 million per resident (Huntington et al., 2012), extensive adaptation for coastal risk reduction is anticipated (Brody et al., 2007). Failure and expensive maintenance of infrastructure that extends to coastal areas portend a significant increase in new nature-based, coastal infrastructure as a means to avert risk and reduce the cost of coastal adaptation. Further, because shoreline armoring is prohibited or significantly restricted in several U.S. states (O'Connell, 2010), nature-based, living shoreline approaches will likely be more frequently used.

There is considerable activity around the world to employ natural and nature-based features (NBBF), which can enhance the CO_2 removal value of coastal adaptation projects (Bridges et al., 2015). Nature-based features mimic characteristics of natural features, but are created by human design, engineering, and construction to provide specific services such as coastal risk reduction. The built components of the system include nature-based and other structures that support a range of objectives, including erosion control and storm risk reduction (e.g., seawalls, levees), as well as infrastructure that provides economic and social functions (e.g., navigation channels, ports, harbors, residential housing). Case studies of demonstrated projects in the United States, Europe, Mexico, and China are emerging from this rapidly growing area of research (see Bilkovic et al., 2017; Bridges et al., 2015; Saleh and Weinstein, 2016; and Zanuttigh and Nicholls, 2015 for reviews). About 14 percent (22,000 km) of the U.S. shorelines have already been armored (Gittman et al., 2015) of the shoreline armored. Converting these armored shorelines to natural shorelines with plants, sediments, and tidal flooding features will provide significant benefits as a NET. However, although implementation of nature-based approaches to tidal wetland creation has reached the deployment level, the estimates for CO_2 removal are based primarily on assumptions that these approaches attain OC accumulation rates similar to those for natural or restored wetlands.

Management of Wetland Transgression into Uplands

Wetland transgression allows the area of tidal wetlands to expand as sea levels rise and increase annual CO_2 removal capacity, especially if erosion of existing tidal wetlands can also be prevented. Coastal mapping and SLR projections of inundation enables identification of potential opportunities for transgression. Schuerch et al., 2018 modeled that wetland gains of up to 60 percent would be possible if transgression can occur in just 37 percent of wetland areas globally, compared to an expected loss of up to 30 percent due to SLR without transgression. However, knowledge is more limited with regard to how current land cover, ownership, and economic value of upland areas will influence the practical potential for transgression. For example, commercially valuable upland is being armored once the flooding risk becomes apparent. Haer et al., 2013 report that inundated land area will increase between 2.6 and 7.6 million ha by 2100, depending on SLR projection and extrapolation method. Assuming 1ft of vertical accretion by 2100, 2, 4, and 6 ft of SLR above MHHW correspond with 1.5, 0.87, and 0.93 million ha, respectively, of net upland (excluding developed land) inundated (NOAA SLR viewer[2]). Managed shoreline retreat strategies that discourage development and decrease population in areas with increasing flood risks and that allow them to flood with coastal waters (Kousky, 2014), not only reduce coastal risks but also increase land area for CO_2 removal. Barriers to managed transgression for wetlands into uplands may vary by upland land-use type. Approximately 43 percent of upland land area between MHHWS (Mean Higher High Water Spring) and MHHWS +2ft is cultivated, with another 20 percent as pasture/hay and grassland (NOAA Office for Coastal Management, 2018). Information about change in areas of inundated developed areas was not available. However, because economic costs of inaction increase over time (Hauer et al., 2016; Reed et al., 2016), coastal adaptation policies for coastal risk reduction could foster a predictable trend for not only identifying additional areas for inland migration and capacity for its management, but also additional areas for other NETs. In other words, similar socioeconomic issues may exist when converting other coastal land uses to coastal wetlands (i.e., restoration).

Management strategies would be needed to maximize the potential expansion of tidal wetlands into uplands. Management of wetland transgression could also include policy measures that both reduce flood risk (Brody et al., 2007) and increase CO_2 removal capacity. However, we lack typologies and rigorous methodologies for predicting where transgression will occur, how existing land uses will allow it, and the cost to protect some potentially large expanses of low-lying coast for wetland expansion. The field lacks knowledge of the OC burial rate trajectory associated with

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[2] See https://coast.noaa.gov/digitalcoast/tools/slr.html.

upland land transgression to wetlands. Upland soils can begin to bury OC at greater rates but productivity of upland species may decline while wetland species invade, with a period of net lower productivity and lower OC burial rates than "natural" coastal wetlands.

Augmentation of Shorelines with Carbon-Rich Materials

Augmenting coastal projects with carbon-rich materials can enhance carbon storage by burying externally-produced carbon-rich materials (e.g., burying wood or biochar) and can increase rates of OC burial by bioengineering wetland species toward lower rates of decomposition (e.g., manipulating lignin content). These approaches could occur in tandem with restoration, coastal adaptation and shoreline protection, and management of wetland transgression.

Direct addition of slow-decomposition forms of OC such as logs and biochar can augment carbon burial. Several studies have evaluated wood burial as a means to increase CO_2 sequestration capacity (Freeman et al., 2012) and biochar addition as a means to reduce nitrogen mineralization of peat and coastal wetlands (Luo et al., 2016; Zheng et al., 2018). The scientific literature also supports the use of carbon-rich materials to increase the CO_2 removal potential of peatlands by "injecting" timber (Freeman et al., 2012). Similarly, decay-resistant conditions of tidal wetlands and seagrass meadows could be harnessed, but further study is needed to evaluate decay rates of different materials and demonstration projects are needed to achieve CO_2 removal at scale. Evidence indicates that the waterlogged wood of ships that has been buried in sediment is often in a very good state of *in-situ* preservation in marine environments (Gregory et al., 2012). Macchioni et al., 2016 found that all samples from wood foundations in Venice, Italy, showed at least 30 percent residual bulk density, with the earliest known construction in 1854. The state of wood preservation is related to several factors, including thickness of the element, depth of burial, horizontal/vertical position, and wood species (Macchioni et al., 2016). A 3-year wood degradation study showed that wood buried below 43 cm was highly protected from decay, with erosion bacteria promoting the loss of surficial wood (<0.5 mm; Bjordal and Nilsson, 2008). Wood burial is only one nature-based example. Constructing revetments or breakwaters with concrete composed of carbon-rich water, aggregate, or embedded wood is another example of a more engineered approach.

Afforestation management strategies for planting mangroves in marsh areas are also under consideration. SLR and warming are leading to increased expansion of mangroves in some areas, suggesting that this or other tree species could be introduced in other areas of transgressing wetlands. To avoid double-counting afforestation gains in wetlands with terrestrial areas, accounting methods based on new remote sensing and field validation research must be developed, which has been identified as an area of improvement for future EPA GHG inventory compilation (EPA, 2017).

Genetically engineering wetland macrophytes to increase their lignin content is another option to enhance wetland OC burial. There has been considerable interest in degrading lignin and altering the lignin content of vegetation to improve the efficiency of cellulosic biofuels production (Wei et al., 2001). The interest for biofuels is to decrease lignin content to increase accessibility of plant polysaccharides to microbial and enzymatic digestion (e.g., Ragauskas et al., 2006), but the interest for coastal blue carbon is to increase lignin content of roots and rhizomes and reduce OC decomposition. Biofuels researchers have identified genes that encode the enzymes leading to the building blocks of lignin (Hoffmann et al., 2003), and have achieved downregulation of some of these genes and hence lignin biosynthesis (Chen and Dixon, 2007; O'Connell et al., 2002; Reddy et al., 2005). The predominantly anoxic conditions in coastal peat sediments allow an accumulation of phenolic compounds from lignin, inhibiting decay by suppressing phenol oxidase enzyme activity and microbial enzymatic decomposition of senescent vegetation (Appel, 1993; McLatchey and Reddy, 1998). Promoting production of phenols and decay inhibitors by genetic modification of plants such as *Sphagnum* that produce phenols has been considered for freshwater environments (Freeman et al., 2012). Physiochemical enhancement to suppress phenol oxidase activity by manipulating oxygen availability, acidification by addition of sulfates, addition of phenolic compounds (peat leachates and polyphenolic waste materials), lowering pH, labile carbon, and inorganic nutrient supply has also been proposed (Freeman et al., 2012).

This new area of consideration is in the research development and demonstration phase. These types of projects will require increased technological capacity to assess the permanence of materials used and could employ adaptive management-based approaches to "learn while doing." They could also employ designed experiments, to understand the conditions where they are best applied, and accelerate progress to deployment at scale. With this approach, ecological concerns and off-site negative impacts associated with hard coastal defenses will persist unless the design enhances wetland functions and improves shoreline processes, because shoreline armoring is prohibited or significantly restricted in several U.S. states (O'Connell, 2010). Other opportunities include using species or phenotypes with higher lignin content or afforestation (in mangrove forests). These opportunities have fewer technological barriers but have potential ecological implications.

IMPACT POTENTIAL

Total Carbon Fluxes under Coastal Blue Carbon

Coastal blue carbon is an approach with near-term readiness and low cost when coastal ecosystems are maintained, restored, created, or engineered with minimal hard infrastructure and for other purposes (e.g., coastal risk reduction, fisheries production). Coastal restoration, adaptation, and management offer the potential to maintain and accelerate the rate of negative CO_2 emissions at a scale of 0.02-0.08 Gt/y CO_2 (Table 2.1). The committee expects the timeframe for readiness for each approach to vary. By 2030, the committee estimates that implementation of several of the management approaches described above can result in annual flux of 0.037 Gt/y CO_2. By 2060, annual flux could reach 0.077 Gt/y CO_2 depending on technological developments, improved scientific understanding, and the ability to overcome societal barriers. Technological advancements that enable successful demonstration and deployment of carbon-rich projects supply about 36 percent of annual flux by 2030 and 43 percent by 2060. Wetland transgression becomes a more important flux over time, increasing to 32 percent by 2100. This section describes the source of these estimates.

The total carbon flux per year, and potential carbon impact of coastal blue carbon is most influenced by the total area of coastal carbon ecosystems, the rate at which they bury OC, and the potential to augment projects and strategies to manage wetland transgression. As described above, the committee considered the following key coastal blue carbon approaches: (1) active ecosystem management; (2) restore coastal wetlands where they have been degraded or lost; (3) convert hardened and eroding shorelines to natural shorelines as part of coastal adaptation; (4) manage wetland transgression into uplands with change in SLR and human drivers/impacts; and (5) increase CO_2 removal capacity by augmentation with carbon-rich materials. The total carbon flux potential is based on the maximum area available to implement each approach, and the sequestration rates of 7.98 t/(ha y) CO_2 for tidal wetlands and 1.58 t/(ha y) CO_2 for seagrass meadows (EPA 2017; SOCCR 2).

Active Ecosystem Management

According to NOAA C-CAP, current estuarine wetland area is 0.22 million ha. Estimating areas of seagrass meadow is more challenging because of knowledge gaps in seagrass meadow distribution, extent, and species identity. The current estimate of seagrass meadow in the United States is 0.24 million ha (SOCCR). The total carbon flux

TABLE 2.1 Total U.S. Annual Carbon Flux for Tidal Wetlands and Seagrass Meadows for Key Coastal Blue Carbon Approaches Evaluated in This Report

		2018	**2030**	**2060**	**2100**[e]
		Flux (Gt/y CO_2)	**Flux (Gt/y CO_2)**	**Flux (Gt/y CO_2)**	**Flux (Gt/y CO_2)**
Active ecosystem management[a]		0.021	0.021	0.021	0.021
Restored[b]			0.002	0.008	0.008
Nature-based adaptation[c]			0.001	0.002	0.002
Managed wetland transgression[d]	0-2ft			0.012	0.012
	2-4ft				0.007
Carbon-rich projects[f]			0.013	0.034	0.008
Total		0.021	0.037	0.077	0.058

[a] Active ecosystem management is unlike other approaches in that maintaining rather than increasing wetland area constitutes negative emissions. However, proactive management is needed to maintain the rates of flux and area. Because of high uncertainty in estimating the decreasing baseline of the current carbon burial rate, the committee did not deduct the baseline when calculating this CO_2 removal number. [b]Twenty-five percent of potential area restored by 2030, full area restored by 2060; [c]25 percent of potential area adapted by 2030, full potential area adapted by 2060; [d]Projected 0-2 ft SLR by 2060 and 2-4 ft SLR by 2100, land area estimate reflects assumption of 1 ft of accretion through 2100; [e]No additional areas for any CO_2 removal approach *except* managed wetland transgression were included in the 2100 scenario. [f]Augmentation of projects with carbon-rich materials implemented at 25 percent potential area for restoration and adaptation projects by 2030, full potential area by 2060 (annual rate based on area of projects implemented by year indicated).

of coastal blue carbon can be estimated from the combined area and rate of OC burial for existing tidal wetlands and seagrass beds. For existing "natural" tidal wetlands and seagrasses, the total carbon flux is currently approximately 0.021 Gt/y CO2 (Table 2.1). To maintain these annual rates, the rate of sequestration per unit area and total area of coastal wetlands would require different levels of management, and in many cases, proactive management. Because of high uncertainty in projecting the future change to the baseline sequestration, the committee did not deduct the baseline when calculating the impact potential for this NET. Instead, the committee used the current coastal carbon burial rate as the CO_2 removal capacity of active ecosystem management to maintain this number.

Restoration of Lost or Degraded Coastal Wetlands and Wetland Creation

The total carbon flux from restoration of coastal wetlands can be estimated using the rate of OC burial applied to the areas within the coastal wetland boundary (under MHHW line) currently in other land uses or where wetland condition has been degraded. Coastal wetlands can be restored through multiple approaches depending on their type, degree of degradation, and geomorphic setting. Each approach has been shown to achieve CO_2 removal at similar or higher rates than existing "natural" tidal wetlands (e.g., Osland et al., 2012). The committee estimated the total potential annual flux from the sum of the annual sequestration for six types of potentially restorable land use types: (1) medium- to high-intensity developed lands (53,938 ha), (2) low-intensity developed lands, open space, and barren land (139,171 ha), (3) cultivated, pasture/hay and grasslands, including tidally restricted lands (317,468 ha), (4) unconsolidated shore (341,721 ha), and (5) recently lost or eroded and converted to open water (125,525 ha; EPA, 2017; NOAA Office for Coastal Management, 2011). Additionally, the area of seagrass meadow estimated to have been lost in the United States provides an opportunity for further restoration (342,943 ha; Waycott et al., 2009). To avoid double-counting of land areas, the committee assumed that developed and cultivated lands approximated the MSL-MHHW extent of the tidal frame, cultivated lands were at approximately MSL, unconsolidated shore occupied the tidal frame from below MSL to 50 ft below mean low water (MLW), and recent open water from 50 ft below MLW to 150 ft below MLW. The committee estimated an annual flux of 0.008 Gt/y CO_2 if all former coastal wetlands were restored and potentially suitable areas used for wetland creation. Because not all former coastal areas could be restored immediately, the committee estimated an annual rate of 0.004 Gt/y CO_2 by 2030 (with 50 percent of the available land area restored) and 0.008 Gt/y CO_2 by 2060 (with all potential area restored). The committee held this rate constant into 2100, even though it depends on maintaining this area of coastal wetlands.

The ability to realize the CO_2 removal potential of these lands will depend on site conditions, elevation, and degree of disturbance. For example, utilizing lands in low-intensity or nonhuman areas may pose the lowest risks to increasing available land for coastal blue carbon because they are not in high demand. Kroeger et al. (2017a) report that 27 percent of former tidal wetlands on the U.S. Atlantic Coast are currently tidally restricted. Much of this area is likely used for agricultural purposes. Converting to coastal wetland from agricultural use may pose greater societal and economic consequences than converting from lands that are of relatively lower intensity (see Chapter 3 for more detail on implications of significant shifts in land use). Although possibly containing eroded or subsided tidal wetlands, unconsolidated shore area may include valuable near-shore habitat that is not suitable for tidal wetland restoration or creation. Some areas may be considered more appropriate for seagrass restoration. Other considerations include changes in coastal policy; for example, if the National Flood Insurance Program (NFIP) adopts a risk-based model, existing areas of developed land with high frequency of losses due to flooding or storm surge may become more readily available for other uses that can sequester OC. These considerations introduce significant knowledge gaps because of the potential variability in the annual carbon flux of restored and created coastal wetlands.

Conversion of Hardened to Natural Shorelines and Stabilization of Eroding Shorelines

The committee used the length of armored shoreline for the United States (22,000 km) and a width of 61 m (used as an approximate tidal range from MSL to 50 ft below MLW) to compute the potential area that could be converted to living shorelines and bury OC. To avoid double-counting with potential restoration areas currently in cultivation and development, the committee used the approximated area occupied by the tidal range below MSL. Replacing the existing length of hardened shorelines (22,000 km) with living shorelines, the committee estimated an annual rate of 0.001 Gt/y CO_2 by 2030. Employing these natural and nature-based measures to prevent erosion of another 22,000 km of existing shoreline would result in an annual rate of 0.002 Gt/y CO_2 by 2060.

Management of Wetland Transgression into Uplands

The committee approximated the following SLR scenarios: 0.68m by 2060, 1.12m by 2100, and 1.68m by 2130 (NOAA Office for Coastal Management, 2011). If the existing tidal wetland areas are maintained in their current state (i.e., keeping pace with SLR), and areas of tidal wetland increase as uplands become inundated by regular tidal flooding (either through assisted management or other means), total tidal wetland area will increase. With 0.68m of SLR, approximately 1.5 million ha of new tidal estuarine wetlands are estimated to develop (NOAA Office for Coastal Management, 2018). At an annual rate of 7.98 t/(ha y) CO_2 for tidal marsh, this equates to 0.012 Gt/y CO_2. Under 1.12m of SLR, an additional area of 0.87 million ha is projected (0.007 Gt/y CO_2), for a total annual flux increase to 0.019 Gt/y CO_2. However, significant uncertainties persist with regard to the fate of tidal wetlands under SLR and future coastal management (Kirwan and Megonigal, 2013). As the leading edge of upland migrating inland becomes marsh, the coastal edge may be submerged and/or eroded, depending on coastal management. The carbon lost from submerged and/or eroding may cause a permanent loss of carbon, be emitted to the atmosphere, or be redeposited on the marsh or mangrove shoreline or bank. Significant erosion of coastal wetlands in areas has already been observed, and projected SLR suggests that new areas will be eroded without management interventions (Figure 2.4). Using an accretion rate of 1 ft by 2100, "open water" area is projected to increase on the order of 1.5-2.0 million acres with each foot of SLR (NOAA Office for Coastal Management, 2018).

Augmentation of NET Projects with Carbon-Rich Materials

Approximately 467,246 ha (the sum of unconsolidated shore and recently eroded wetland areas) of land is available for restoration, which could incorporate carbon-rich materials to increase elevation to an appropriate level for persistence of wetland vegetation. If carbon-rich materials were supplied at the same rate that restoration and adaptation projects were implemented, and included as part of managed wetland transgression strategies (50 percent by 2030 and full area by 2060), the annual flux would reach 0.007 Gt/y CO_2 by 2030 and 0.027 Gt/y CO_2 by 2060 (based on augmenting with carbon-rich materials to 1.5 ft for restoration projects in unconsolidated shore areas and 3 ft in recently eroded wetlands, 3 ft for coastal adaptation projects, and equivalent of 1 ft stocks in strategies for managed wetland transgression). The addition of carbon-rich materials is an opportunity for carbon storage and not for carbon removal. Thus, annual rates were obtained by dividing the total storage capacity of this level of project implementation by the number of years the projects will occur (up to 2100 in this scenario).

Summary of Coastal Blue Carbon Estimates

Combining the annual fluxes for each approach based on the potential rate at which they could be implemented, the committee estimated an annual carbon flux rate for the four time horizons: current (2018), 2030, 2060, and 2100. Total potential annual flux was estimated as 0.021, 0.037, 0.077, and 0.058 Gt/y CO_2, respectively (Table 2.2; Figure 2.6).

Total U.S. potential carbon removal capacity is the magnitude of OC burial rates, should all potential activities identified by the committee be implemented and rates of OC sequestration maintained over the specified time horizons. Although global areas of coastal tidal wetland and seagrass vegetation have been estimated and annual rates applied to derive global carbon capacity of existing areas, little is known about the global capacity if these restoration, creation, and nature-based engineering approaches were applied at a global scale.

TABLE 2.2. Total U.S. (cumulative) potential carbon capacity for tidal wetlands and seagrass meadows

		2018	**2030**	**2060**	**2100**[f]
		Capacity (Gt CO_2)	**Capacity (Gt CO_2)**	**Capacity (Gt CO_2)**	**Capacity (Gt CO_2)**
Active ecosystem management[a]		0.021	0.233	0.868	1.714
Restored[b]			0.023	0.265	0.591
Nature-based adaptation[c]			0.006	0.068	0.152
Managed wetland transgression[d]	0-2ft			0.496	0.980
	2-4ft				0.561
Carbon-rich projects[e]			0.148	1.123	1.426
Total		0.021	0.410	2.820	5.424

[a] Active ecosystem management is a critical CO_2 removal approach unlike other approaches in that maintaining rather than increasing wetland area constitutes negative emissions. However, proactive management is needed to maintain their rates of flux and area. [b] 25% of potential area restored by 2030, full area restored by 2060; [c] 25% of potential area adapted by 2030, full potential area adapted by 2060; [d] Projected 0-2ft SLR by 2060 and 2-4ft SLR by 2100, land area estimated includes assumption of 1ft of accretion through 2100; [e] Augmentation of projects with carbon-rich materials implemented at 25% potential area for restoration and adaptation projects by 2030, full potential area by 2060 - values are cumulative; [f] No additional areas for any coastal blue carbon approach EXCEPT managed wetland transgression were included in the 2100 scenario.

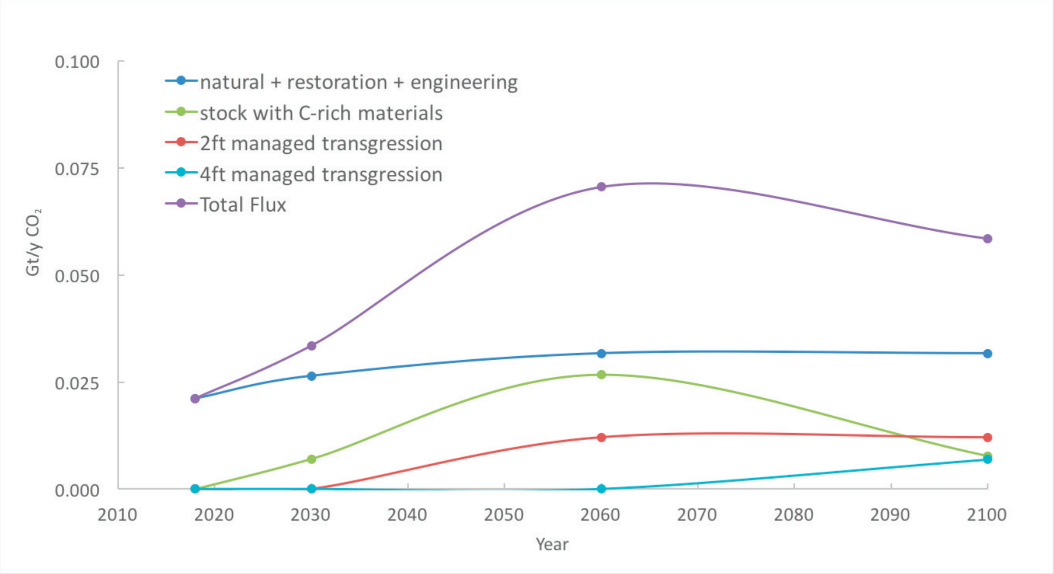

FIGURE 2.6 Annual CO_2 flux (Gt/y) for coastal wetland CO_2 removal approaches: (a) natural, restoration, and nature-based coastal adaptation, (b) restoration and nature-based coastal adaptation augmented with carbon-rich materials, (c) managed wetland transgression for 0-2 ft and 2-4 ft of SLR, and (d) total cumulative annual flux of all coastal blue carbon approaches combined.

Existing coastal ecosystem management areas yield an estimated potential carbon capacity of 0.233, 0.868, and 1.714 Gt CO_2 by 2030, 2060, and 2100, respectively. Tidal wetland and seagrass areas that could be restored yield another 0.023, 0.265, and 0.591 Gt CO_2 by 2030, 2060, and 2100, respectively. These estimates assume that areas that could be restored within the coastal boundary (below MHHW) are restored at 25 percent total area by 2030 and 100 percent total area by 2060. The estimate does not include any new projects beyond 2060, which would increase the total 2100 capacity. Nature-based adaptation projects yield an additional 0.006, 0.068, and 0.152 Gt CO_2 by 2030, 2060, and 2100, respectively. This estimate also does not include new projects beyond 2060, which would increase the total 2100 capacity. Managed wetland transgression adds another 0.496 Gt CO_2 by 2060 (with 0.68 m SLR) and 0.980 Gt CO_2 by 2100 (with 1.12 m of SLR). Finally, augmenting shorelines with carbon-rich materials, implemented at the same rate as described, yields another 0.148, 1.123, 1.426 Gt CO_2 by 2030, 2060, and 2100, respectively. Thus, the total potential capacity for coastal carbon is 0.410, 2.820, and 5.424 Gt CO_2 by 2030, 2060, and 2100, respectively.

Other Radiative Impacts

Methane

Restoration of tidal wetlands from drained upland and impounded fresh wetlands provides extra benefit to negative carbon emissions, which is the reduction of CH_4 emissions from ditches in these areas. Generally, tidal restrictions such as roads or undersized culverts increase GHG emissions because they either drain the wetland, causing CO_2 emissions, or they cut off the input of the saline water needed to inhibit CH_4 emissions. The supply of tidal saline water is often associated with sulfate that inhibits methanogenesis as sulfate reduction overpasses carbon reduction as electron donors (Poffenbarger et al., 2011). Therefore, salinity has been frequently used as a proxy for estimating CH_4 emissions. Restoration of tidal connections to currently impounded wetlands could decrease CH_4 emissions of 7.9-41.1 (g/(m^2 y) CH_4) (Kroeger et al., 2017a), or 739-3,843 g/(m^2 y) CO_2 when converted to CO_2e by a factor of 34 (CH_4 global warming potential, IPCC, 2013). On the U.S. Atlantic coast, if 2,650 km^2 wetlands could be restored, the CH_4 benefit would be 2.0-10.2 Mt/y CO_2.

Nitrous Oxide

Nitrous oxide (N_2O) is another potent GHG with a global warming potential of 298 (IPCC, 2013). N_2O is produced largely by the denitrification process in wetlands and saturated uplands. The salinity and sulfate in tidal wetlands suppress the production of N_2O. Therefore, the N_2O emissions in tidal wetlands are very small compared with CO_2 and CH_4 fluxes, about an order of magnitude less than CH_4 fluxes (Martin et al., 2018; Murray et al., 2015).

Albedo

Land-use and land-cover changes can change the albedo, or reflectivity, of Earth's surface, and thereby change the radiation balance. There is little difference in albedo for various wetland plants. The albedo of flooded salt marsh is ~0.089 (Moffett et al., 2010), slightly higher than ocean water. Considering the small total area of coastal wetlands not only for the United States, but also for the world, coastal carbon approaches would have a trivial effect on the overall global radiation balance, considering albedo alone.

SECONDARY IMPACTS

Ecosystem Services

Tidal wetlands and seagrass meadows provide ecosystem services (Barbier et al., 2011), which are broadly defined as "the benefits people obtain from ecosystems" (MEA, 2005a). Examples of services provided by coastal ecosystems include recreation and tourism, key fishery habitats, improved water quality, and flood and erosion mitigation. Each has monetary and nonmonetary value, which can reduce risks to life, property, and economies (Barbier et al., 2011; Duarte, 2000; Lovelock et al., 2017; Mcleod et al., 2011). As described above, these coastal ecosystems are maintained, restored, used for nature-based adaptation, and managed to enable wetland transgression into uplands to provide ecosystem services as well as remove CO_2.

Although ecosystem services in coastal ecosystems are well documented, data on their monetary and nonmonetary values are limited. Where monetary value exists, it has proven difficult to bring the services to the marketplace, with the exception of carbon in mangroves (Jerath et al., 2016). The value of services provided by tidal marsh has been extensively studied, but less is known about seagrass meadows (Table 2.3; Barbier et al., 2011; Craft et al., 2009; Gedan et al., 2009; Orth et al., 2006; Waycott et al., 2009). Even before consideration of its market value for carbon removal, watershed restoration provides a 3:1 (CPRA) to 8:1 (Sklar, presentation to committee) return on investment. The National Science and Technology Council released a report on research needs for coastal green infrastructure to improve assessments of ecosystem services (NSTC, 2015).

Risks of Coastal Blue Carbon

Some of the coastal blue carbon approaches considered here pose risks that will influence where and how they are deployed (e.g., large fill volumes, subtidal areas, coastal landscape processes). These risks include:

- potential for sediment contaminants, toxicity, bioaccumulation and biomagnification in organisms,
- issues related to altering degradability of coastal plants,
- use of subtidal areas for tidal wetland carbon removal,
- effect of shoreline modifications on sediment redeposition and natural marsh accretion, and
- abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for carbon removal.

TABLE 2.3 Ecosystem Service Value Examples for Coastal Blue Carbon

Ecosystem service	**Ecosystem process or function**	**Ecosystem service value example**		
		Mangrove	**Seagrass Meadow**	**Coastal Marsh**
Raw materials and food provisioning	Generates biological productivity and diversity	\$484-595/ha/y (2007 USD)	N/A	£15.27/ha/y (1995 GBP[a])
Natural hazard regulation	Attenuates and/or dissipates waves	\$8,966-10,821/ha/y (2007 USD)	N/A	\$8,236/ha/y (2008 USD)
Regulation of erosion	Provides sediment stabilization and soil retention in vegetation root structure	\$3,679/ha/y (2001 USD)	N/A	N/A
Regulation of pollution and detoxification	Provides nutrient and pollution uptake, as well as retention, particle deposition	N/A	N/A	\$785-15,000/acre/y (1995 USD)
Maintenance of fisheries	Provides sustainable reproductive habitat and nursery grounds, sheltered living space	\$708-987/ha/y (2007 USD)	\$19/ha/y (2006 AUD[b])	\$981-6,471/acre/y (1997 USD)
Organic matter accumulation	Generates biogeochemical activity, sedimentation, biological productivity	\$31/ha/y (2011 USD)	N/A	\$30.5/ha/y (2011 USD)
Recreation and aesthetics	Provides unique and aesthetic submerged vegetated landscape, suitable habitat for diverse flora and fauna	N/A	N/A	£33/person/y (2007 GBP)

[a] GBP: Great Britain pounds; [b] AUD: Australian dollars.

SOURCE: Modified from Barbier et al., 2011.

The U.S. Army Corps of Engineers (USACE) uses Ocean and Inland Testing Manuals (OTM and ITM) and tiered approaches to evaluating toxicity issues associated with dredged materials in accordance with the Food and Drug Administration Action Levels for Poisonous and Deleterious Substances in Fish and Shellfish for Human Food and the Water Resources Development Act of 1999. The USACE follows Section 103(b) of the Marine Protection, Research and Sanctuaries Act in choosing placement sites designated by EPA to reduce human and environmental impacts to the maximum extent possible (EPA, 1991).

The alteration or degradation of the wetland plant community raises significant ecological questions. Most coastal fisheries of the U.S. East and Gulf of Mexico coasts are estuarine-dependent, that is, they rely on tidal wetlands as nursery grounds for juvenile development. At some stage, most of these organisms depend on wetland vegetation-derived detritus. Changing the lignin content of the detrital feedstock could negatively impact secondary production of the entire coastal zone. The social and economic impacts of introducing genetically modified plants into the coastal zone must be evaluated before or alongside any research agenda on lignin modification to investigate at what point, if any, marsh survival based on increased lignin content balances the alteration of coastal fisheries and dependent human livelihood.

Societal Impacts

There may also be significant societal barriers to conversion of flood-prone lands to wetlands despite the increasing coastal risks of flooding. To overcome these barriers, managers must plan and design the coast in a way that allows for continued development by humans while enhancing carbon removal capacity of larger areas of wetlands (Stark et al., 2016). However, the rising risk of flooding and storm damage in coastal zones may lead to regulatory changes that reduce the financial burden on the federal government and disincentivize coastal development. Coastal hazards significantly increase risks to people and infrastructure. For example, the cumulative cost of the $16 billion weather events in the United States in 2017 was $306.2 billion (NOAA National Centers for Environmental Information, 2018). As a result of Superstorm Sandy, Hurricane Katrina, and the events of 2017, the Federal Emergency Management Agency (FEMA) has incurred more than $24 billion in debt (CBO, 2017) with additional borrowing expected.

As regulatory agencies better enable restoration and nature-based adaptation projects, efforts to safeguard against land reclamation may create a socioeconomic barrier (Chee et al., 2017). The difference between wetland creation for coastal adaptation (wetland reclamation) and land reclamation is distinct but may be blurred by uninformed policy or unenforced policies. As a best practice, assurances that coastal restoration and nature-based adaptation projects are intended to build wetlands for effective carbon removal rather than to develop land in the coastal zone should be built into the regulatory framework.

Other Barriers

This report addresses the permitting mechanisms that exist for deployment of NETs. However, the permitting process should be improved. For example, the USACE process takes on average more than 300 days to complete (USACE, 2017). In 2016, a NW54 was approved to expedite living shoreline or coastal bioengineering projects. Projects eligible for this expedited permit review are limited to 30 ft depth from shoreline and 500 ft length (USACE, 2017). Identification of ways to accelerate regulatory approval of projects that also safeguard robust and effective carbon removal is a critical need.

ESTIMATED COSTS OF IMPLEMENTING COASTAL BLUE CARBON

The costs to implement the different coastal blue carbon approaches vary widely and largely depend on project size, intervention type, design and construction costs, materials costs, costs to transport materials and equipment, and monitoring carbon removal. However, if such projects occur regardless of carbon removal potential, because of the multiple ecosystem services and coastal adaptation functions they confer, then only the incremental costs for monitoring carbon removal needs to considered.

Incremental Costs for Monitoring Coastal Blue Carbon

If projects are implemented for purposes other than or in addition to carbon removal, then costs are reduced to the incremental cost of monitoring coastal carbon removal. Such costs approximate \$0.75/t CO_2 for tidal wetlands and \$4/t CO_2 for seagrass meadows) for all coastal blue carbon approaches, except those augmented with carbon-rich materials (estimated at \$1-30/t CO_2) depending on the material and construction method used. To estimate those monitoring costs, the committee considered the costs associated with existing coastal and terrestrial monitoring networks that include coupled remote sensing and plot-based measurements. For example, the California Forest Change Detection Program has achieved a cost of \$0.004/ha through agency efficiencies and leveraging staff across programs (Fisher et al., 2007a). The monitoring needs for coastal blue carbon would not be limited to land change detection, which represents the minimum cost. A relevant example of a comprehensive monitoring program is the Coastwide Reference Monitoring System (CRMS), which is a mechanism to monitor and evaluate the effectiveness of projects conducted under the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) in Louisiana at the project, region, and coastwide levels (Steyer et al., 2003). The network provides multiple forms of data and research for a variety of user groups, including resource managers, academics, landowners, and researchers. The estimated cost of this research and monitoring program is \$80/ha or \$6/(ha y) based on projects funded thus far.[3] Monitoring system costs reported for national-level programs were reported as \$0.50 to \$5.50/ha (Böttcher et al., 2009). Recognizing that the CRMS includes research, the incremental cost of monitoring may be lower.

RESEARCH AGENDA

The committee developed a research agenda with the overarching goal to preserve and enhance the high rates of OC sequestration in existing tidal wetlands and seagrasses in the coastal zone and to expand the area covered by these ecosystems. As discussed earlier, carbon sequestration rates can be enhanced through a combination of management activities that depend on

- increasing the OC density in soils of coastal systems,
- retarding edge erosion of existing wetlands,
- increasing aerial expanse of wetlands through transgression into upland areas as these areas become flooded by the sea,
- augmenting mineral sediment availability to ensure wetland elevation remains in balance with increasing rates of SLR,
- hybrid “engineering” (restoration, creation, coastal adaptation) approaches that enhance carbon removal and maintain or improve coastal ecosystem services, and
- augmenting soils with high concentrations of slowly degrading OC such as biochar or logs.

The research agenda also examines technological needs and the feasibility of carbon removal as part of coastal protection projects designed to minimize exposure of human systems to the risk of storms and floods. The research is recommended to reduce the barriers to reaching 1 GT CO_2 scale deployment in the United States as well as the

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[3] Based on projects listed on the CWPPRA website for 2005-2019. See https://www.lacoast.gov/new/Projects/List.aspx.

largest uncertainties associated with the processes that most affect annual carbon removal and capacity.

The research agenda spans basic science research on carbon removal potential, carbon transformation, and permanence under different approaches as well as socioeconomics and policies associated with converting land for carbon removal. A proposed framework to accelerate deployment of approaches that increase wetland area through restoration, creation, nature-based adaptation, and managed wetland transgression at scale combines designed experimental research, demonstration sites, and adaptive management of engineered projects. Designed research enables rigorous tests of approaches, demonstration sites enable tests of augmenting projects with carbon-rich materials, and adaptive management enables modification of technology and engineering or management parameters when projects do not meet expected performance criteria. Some proposed approaches will have implications for measurement of species diversity and productivity in the coastal zone. Finally, social science research will investigate both the implications of these projects and the social barriers to achieving them at scale. The research agenda components are described in detail below, and their costs are summarized in Table 2.4.

Basic Research

Research is needed that will address some of the key uncertainties in understanding and using coastal ecosystems as a NET, including but not limited to (1) the fate of OC fixed in coastal ecosystems; (2) the changes in areal extent of coastal ecosystems in response to climate change, SLR, and human disturbance, and (3) genetic engineering or selection of high OC density materials and coastal plants that decay slowly in coastal sediments. The committee envisions a comprehensive research program at a similar scale to NOAA's national sea grant program budget.

The fate of OC produced and buried in soils/sediment of coastal ecosystems

Basic research is required to reduce uncertainties in how changes in sea level, climate, and human activities will impact the primary production, ecosystem respiration, and long-term burial of OC in coastal wetland ecosystems. Our current understanding and ability to predict carbon burial rates in existing coastal wetland ecosystems is limited, and predicting how rates will change is an important challenge. Research should be designed to take advantage of existing strong gradients in OC burial rates, tidal amplitude, biogeographic province/wetland species composition, climate, sediment

TABLE 2.4 Costs and Components of a Coastal Blue Carbon Research Agenda

	Recommended Research	**Estimated Research Budget ($M/y)**	**Timeframe (year)**	**Justification**
Basic Research	Basic research in understanding and using coastal ecosystems as a NET	6	5-10	5 projects at $2M/y for 10 years to address fate of OC produced and buried in soils/sediments of coastal ecosystems; 5 projects at $2M/y for 10 years to address change in area coastal blue carbon ecosystems in response to change in major climate change or SLR and management drivers; 5 projects at $2M/y for 5 years to address selection of materials and coastal plants/ phenotypes producing high OC density materials with slow decay rates buried in coastal sediments carbon.
Development	Mapping current and future (i.e., after SLR) coastal wetlands	2	20	Former NASA CMS projects (wetland: $1.5M/y; seagrass $500K/y)
	National Coastal Wetland Data Center, including data on all restoration and carbon removal projects	2	20	Scale of NSF Sustainability Research Networks

TABLE 2.4 Continued

	Recommended Research	**Estimated Research Budget ($M/y)**	**Timeframe (year)**	**Justification**
Demonstration	Carbon-rich NET demonstration projects and field experiment network	10	20	Carbon-rich NET demonstration projects and field experiment network (15 sites funded at $670K/site/y)
	Integrated network of coastal sites for scientific and experimental work on carbon removal and storage	40	20	15 engineered sites at a cost of $1M/y per site (approximate funding for an LTER); 20 augmented managed and engineered sites at a cost of $500K/y; 8 new managed sites at $500K/y (wetland transgression – 0-2 ft and seagrass); 5 U.S. scale synthesis activities (wetland: 3; seagrass: 2) at a cost of $200k/y per activity.
Deployment	Coastal blue carbon project deployment (social science, economic and policy research on incentives and barriers)	5	10	Policies, incentives, and barriers will change as coastal risk increases.

NOTE: CMS = Carbon Monitoring System; LTER = Long-Term Ecological Research; NASA = National Aeronautics and Space Administration; NET = Negative Emissions Technology; OC = organic carbon; SLR = sea level rise.

availability, direct local human activities (e.g., nitrogen enrichment) to develop models with universal application. A combination of field, lab experiments, and modeling activities would be appropriate in conducting this research. *Potential funders: National Science Foundation Division of Environmental Biology (NSF DEB), Chemistry & Materials Science), USACE, Department of Energy (DOE), industry research and development (R&D), architecture and engineering (A&E) firms, foundations. Research budget: $2M/y over 10 years.*

The change in areal extent of coastal ecosystems through the remainder of the 21st century in response to changes in major controlling drivers, such as climate change, sediment availability, SLR, and human disturbances

Coastal wetland ecosystems are being heavily impacted, and their areal extent is changing rapidly as a result of rapidly changing rates of SLR, sediment availability, and other factors. The fate of existing systems and whether they will decrease in areal expanse because of edge erosion or drowning or increase in areal expanse in conjunction with transgression into upland areas as they flood with rising seas is poorly understood. The ability to predict areal expanse is of paramount importance because of its effect on the future carbon removal trend. Research should be conducted to develop mechanistic and predictive understanding of these dynamics in the future. A research program should be developed to improve understanding and prediction of the extent of the coastal wetlands under multiple stresses. *Potential funders: NSF DEB, NSF Division of Ocean Sciences (OCE), DOE, NASA. Research budget: $2M/y over 10 years.*

Selection of plants/phenotypes able to produce high OC–density tissues as well as other OC materials that resist decay in coastal ecosystem sediment carbon and slow-decay species/phenotypes used in enhancing coastal carbon

There is little knowledge about the preservation of OC-rich materials in coastal sediments and the capacity to increase their production by new strains/phenotypes of coastal plants. Research is needed to better understand the decomposition and preservation capacity of OC-rich materials such as wood logs and biochar. Research should be conducted to investigate the feasibility and ecological costs and benefits of introducing new plants/phenotypes/genotypes able to produce greater amounts of less degradable tissues. Genetic research could increase lignin content of existing wetland plants. Also needed is a program to improve the technological readiness of using carbon-rich materials, in some cases with new lab-scale experiments, including materials science. Multi-omics research should be supported to better understand how lignin decomposition is related and controlled by microorganisms (Billings et al., 2015) and environmental variation. *Potential funders: NSF (engineering and infrastructure programs, DEB, Chemistry & Materials Science), USACE, DOE, industry R&D, A&E firms, foundations. Research budget: $2M/y over 5 years*.

Development

Mapping transitions in wetland and seagrass land cover and land use due to SLR and other drivers

More work is needed to develop and refine remote-sensing approaches to estimate potential areas for restoration, nature-based adaptation, and wetland elevation gain, wetland productivity, wetland OC burial, edge erosion, and transgression into uplands in the future. Current approaches are labor intensive in the field and lab. Remote sensing offers the opportunity to scale efficiently, to improve accuracy, and be able to better predict and map existing and potentially available coastal wetland areas for carbon removal. For existing, transgressing, and restored tidal wetlands, knowledge gaps persist in mapping salinity boundaries, which reduces the ability to predict CH_4 and CO_2 emissions and uptake. Similarly, for seagrass meadows, OC accumulation rates are roughly understood, but the ability to map and monitor their areal extent is limited. Other key research needs include development of robust typologies that coincide with scenario modeling to identify and project vulnerable land areas where management and restoration should be focused. Finally, developing new methods to account for forested/afforested wetlands along tidal boundaries (i.e., differentiating them from terrestrial forest) in areas where wetlands are transgressing is another key research need.

Further technological development of mapping and remote-sensing tools, as well as field-validated modeling to derive more robust relationships and constrain variability in detecting coastal classifications fundamental for carbon removal (e.g., project types, salinity, soil accretion), are recommended. Research efforts should prioritize long-term research sites. Research sites should be augmented with long-term data to support remote-sensing applications. *Potential funders: NASA, DOE, NOAA, U.S. Forest Service (USFS), EPA. Research budget: $2M/y (tidal wetland: $1.5M; seagrass: $500K) for 5 years.*

Development of a Comprehensive Coastal Blue Carbon Projects Database

A strategy is needed to develop a robust means to verify and catalog number, types, size, cost, engineering specifications, and performance of coastal blue carbon approaches. Best management practices may include design criteria and performance functions associated with technological and ecological specifications of projects. The database will be useful for developing and testing predictive models of coastal blue carbon ecosystem extent and CO_2 sequestration rate. It will also be critical for evaluating the conditions under which carbon removal is optimized, so that adaptive management can be facilitated.

The committee recommends:

- development of an integrated project data repository
- design guidelines for coastal blue carbon with emphasis on coastal restoration, nature-based adaptation, and management of wetland transgression approaches that are most cost-effective, including levels of technical readiness and best management practices
- policy instruments for implementation, monitoring, and assessment, including a catalog of the number, types, size, ecological and geophysical site conditions, and performance of coastal blue carbon approaches and assessment of associated resource requirements

The ”Blue Carbon Research Coordination Network” is developing a comprehensive database of carbon data and some online resources catalog living shoreline projects, but with only limited quantitative data and no comprehensive project and data repositories of this type. *Potential funders: NSF, EPA, U.S. Fish and Wildlife Service (USFWS), USACE, NOAA, state agencies. Research budget: $2M/y for 20 years, with an interagency–academia–nongovernmental organization (NGO)–industry program work group.*

Demonstration

Coastal blue carbon demonstration projects and field experiment network

Demonstration of carbon-rich projects will serve to justify and prioritize approaches that are the most cost-effective for increasing CO_2 removal capacity. Field-scale experiments should take advantage of the extreme range in environmental conditions and settings in which U.S. coastal carbon ecosystems exist to facilitate understanding of basic processes, such as OC burial rates and long-term decay rates of carbon-rich materials under waterlogged, saline conditions. Multiyear studies of low-risk, high-carbon species or phenotypes should also be conducted. Field experiments should involve augmenting a subset of existing natural, restoration, eroding, and adaptation demonstration sites to test carbon-rich approaches in mesoscale field projects. *Potential funders: NSF (engineering and infrastructure programs, DEB), NOAA, USACE, DOE, industry R&D, A&E firms, foundations. Research budget: new field experimental network of demonstration projects that accelerate carbon removal: $10M/y for 20 years.*

Carbon removal systems field experiments and adaptively managed site network (managed and engineered sites)

For "engineered" projects (i.e., wetland restoration and creation and nature-based coastal adaptation), knowledge gaps exist about the various management approaches to sustain the rates of OC accumulation reported in case studies. Although the number and coverage of wetland restoration projects have increased, few studies have considered the long-term OC rates under different settings and project types, typologies guiding implementation (Dürr et al., 2011), and best management practices for monitoring and evaluating the carbon removal performance or response to SLR. Such projects have been implemented since the 1950s, but few studies have answered the suite of research questions that have been so rigorously applied for "natural" coastal systems. For example, intervention projects that integrate artificial and natural features for coastal defense often focus on biological habitat or diversity rather than carbon sequestration (Firth et al., 2014). Given the likelihood of increasing numbers of projects to protect coastlines, this research infrastructure serves to address both technological issues with engineering coastlines for increasing carbon removal capacity and testing and demonstrating performance of existing and new projects. Further, an understanding of how adaptation projects that reduce risks to people and infrastructure can increase and accelerate carbon removal over time, while also preserving and enhancing other ecosystem services, is needed. What remains uncertain is the ability of large-scale shoreline modifications, in areas reliant on sediment resuspension and redeposition for marsh accretion, to maintain the marsh platform and wetland function in the long-term. The committee is unaware of any surface elevation tables (SETs) or long-term estimates of OC accumulation from projects that have applied nature-based approaches to coastal risk reduction, and few estimates from created wetlands.

Research is also needed to understand better how to manage wetland transgression and erosion. Such research should investigate the underlying processes for enhancing OC burial with different management activities or that enable wetland transgression to occur, as well as the costs, benefits, and socioecological system scenarios and responses to inform prediction of trajectories and variability in OC burial over time. Although management of wetland transgression could provide immense new areas of wetlands to bury OC and remove carbon, less is known about OC accumulation rates achieved under these conditions. Using adaptive management, corrective action can be applied if management activities do not maintain OC accumulation rates.

Uncertainties about predictions of engineered wetland performance and wetland survival may create a barrier to any coastal blue carbon approach without sustained and new research, utilizing an adaptive management approach that enables planning, trial and error, and corrective actions if performance criteria are not met (Zedler, 2017). Although soil OC burial for coastal blue carbon is considered an incremental cost of coastal resilience projects, a monitoring network would need to be implemented. This network would consist of landscape-level research on management interventions, coupled soil-decay models to forecast outcomes, and empirical field measurements for validation. All such research should be designed to maximize transfer of technologies and approaches to multiple coastal settings. The research objectives include (1) optimizing of OC burial in transgressing wetlands with a suite of structural and non-structural management approaches, (2) forecasting effects of SLR and sediment availability on trajectories and thresholds of wetland elevation gain and OC burial, and (3) understanding radiative gas emissions in new marshes created by SLR-induced transgression. The field would also benefit from better understanding of the OC balance of uplands as they transition to tidal wetlands. Little is known of the trajectory of upland plant productivity, OC accumulation, and OC fate during the onset of tidal flooding, exposure to saline seawater, and conversion to tidal wetland. Demonstrations/deployments should be conducted across the major upland land-use and land-cover categories likely to be inundated by the sea during the 21st century.

Development of research infrastructure across new engineered and managed sites, and augmentation at existing sites, is needed for a combination of field experiments, networked across adaptively managed projects for accelerated deployment, and coupled with modeling and synthesis efforts. Designed research and field experiments would include observations across networked sites with statistical sampling applied across gradients of project type, coastal biogeomorphic conditions, watershed management, SLR, and climate change exposure. At a minimum, the specific research infrastructure needs includes plot-to-atmosphere measurements of CO_2 and CH_4 fluxes coupled with remote sensing, eddy flux measurement sites for CO_2 and CH_4, a micrometeorological station, water level and salinity instrumentation, an array of SETs, and vegetation plots. An integrated research network across existing NSF/LTER coastal sites, NOAA/National Estuarine Research Reserve Association (NERRA) sites, and NSF/National Ecological Observatory Network (NEON) coastal sites is recommended, with consistent and comparable monitoring of carbon removal rates across sites, by augmenting existing sites with some research infrastructure already in place. Long-term research sites in managed areas anticipated for wetland transgression with up to 2 ft SLR, near-shore submerged aquatic areas (i.e., seagrass), and engineered projects should be prioritized. Efforts should leverage known adaptive management research infrastructure such as CRMS in coastal Louisiana. This research should identify and prioritize approaches that are most cost-effective (minimal infrastructure and negative impacts) for improving CO_2 removal capacity and other ecosystem services. Data synthesis activities are needed to evaluate knowledge gaps, update the state of knowledge as new research results become available, and scale knowledge up to the regional levels. Synthesis products would inform the efforts of a multiregion, inter-organization (agency–academic–NGO–industry) work group to develop a framework for an adaptive management plan, identify projects and common research protocols for carbon removal and other ecosystem services, and identify a common set of SLR and climate change scenarios and models. *Potential funders: NOAA Sea Grant, NSF multiple directorates, DOE, NASA, USFWS, USACE, state agencies, foundations. Research budget: $30M/y for 20 years.*

Deployment

Socioecological and economic research to quantify the costs and benefits of coastal blue carbon

Numerous social and policy aspects emerge from coastal blue carbon approaches, particularly related to land-cover and land-use change. Social barriers are not well understood, particularly in the context of new policy initiatives to reduce costs incurred with increasing coastal risk. Social acceptance of allowing wetlands to transgress into upland areas is highly uncertain (Brody et al., 2012). Other socioecological knowledge gaps include how anticipatory decision-making and managed shoreline retreat strategies could be incentivized (e.g., "true" value of risk reduction rather than insurance based) for coastal risk reduction. As regulatory agencies better enable restoration and nature-based adaptation projects, efforts to safeguard against land reclamation may create a socioeconomic barrier to implementation (Chee et al., 2017). The difference between wetland creation for coastal adaptation (wetland reclamation) and land reclamation is distinct but may be blurred by uninformed policy or unenforced policies. As a best practice, assurances that coastal restoration and nature-based adaptation projects are intended to build wetlands for effective carbon removal rather than to develop land in the coastal zone should be built into the regulatory framework.

Research is needed on the barriers to, and incentives for, increasing the area available for coastal blue carbon and potential impacts of coastal wetland reclamation as a type of carbon removal (e.g., numerous studies illustrate biodiversity risks associated with sea walls that reduce tidal mudflat area). Such social science and policy research could address questions, such as:

- If the ecosystem services value derived from coastal wetland reclamation is added, what are the trade-offs and what governance/policies are necessary to manage against unintended outcomes?
- What would be added costs for permitting (and to USACE/state/local agencies)?

If coastal restoration projects are implemented to enhance ecosystem services other than carbon removal, then the \$/t CO_2 cost for carbon removal is merely the incremental cost of monitoring. However, costs may differ between coastal projects that do and do not consider carbon removal. For example, it may cost more to implement a coastal adaptation structural strategy that sequesters CO_2 (natural or nature-based infrastructure) than one that is more typical (seawalls). Continued research at the local and regional levels is needed to identify approaches to project coastal vulnerability that integrates robust information based on modeling and field measurements of OC accumulation on lands made available through managed shoreline retreat.

Building and promoting coastal carbon as a NET does not depend on a carbon price, because most wetland restoration and coastal adaptation projects are conducted without concern for CO_2 mitigation. Research that quantifies the cost-benefits of coastal blue carbon may incentivize governments to convert lands exposed to coastal flooding to wetlands or private property owners to abandon vulnerable properties (e.g., NFIP repetitive loss properties) and land uses (e.g., agriculture, low-density lands) in lieu of other ecosystem services, and ultimately release those lands for carbon removal. Further, scientists should evaluate the economic co-benefits of wetland restoration/creation/protection. They also need to enhance their understanding of ways to align the timing of expenditures on wetland actions to decrease vulnerability with the benefits accrued to local governments and citizen taxpayers.

Given the paucity of social science, economic, and policy research to date, numerous socioeconomic issues pose barriers to deploying coastal blue carbon at scale. Researchers should explore socioecological and economic linkages among actions to protect, restore, and expand tidal wetlands and human well-being:

- What combinations of federal, state, and local decision-making are most effective, cost-efficient, and protective of local community property rights and values while decreasing community vulnerability to SLR and storm damages?
- How will market forces influence land use in coastal areas? What are the costs and benefits of regulatory vs market-based approaches to wetland management?

The field would benefit from a typology to better predict the likelihood of individual parcels of property by county becoming wetland (actively and passively) as sea level rises. The typology will likely consider factors such as

- trends in local land-use change, property values, major sources of local government revenue, and extent to which marsh management can reduce property damage from storms and SLR,
- current extent of development, existing open space, and future cost of maintaining infrastructure under a scenario of climate change and SLR, and
- politics or people's attitudes about the conversion of property to wetlands.

Finally, research is needed on how:

- decisions on risk avoidance are made and whether that varies in relation to the risk timeline,
- availability of resources influences community/local adaptive opportunity and capacity, and
- adaptive options involving wetlands impact local government revenue and finances.

Potential funders: NSF multiple directorates, NOAA, EPA, state agencies, foundations. Research budget: $5M per year for 10 years.

Monitoring and Verification and Research Management

The cost of coastal blue carbon ($/tCO$_2$) includes the incremental cost of monitoring (described above).

Time delays in fundraising, plan review, and construction should be considered when estimating planning timelines. Research oversight and coordination is embedded within the research agenda cost. Recommendations include developing (1) a multiagency (federal, state, local agencies and academic institutions) working group charged and funded to oversee and integrate research efforts and (2) wetland mitigation-type policies that assess performance based on criteria for best implementation/management practices.

SUMMARY

Coastal wetlands are extremely productive ecosystems; they act as long-term carbon sinks by removing carbon from the atmosphere through photosynthesis and storing it in their soils for long time periods. Compared to other ecosystems, coastal wetlands sequester a very high amount of carbon per unit area: 7.98 t/(ha y) CO_2 for tidal wetlands and 1.58 t/(ha y) CO_2 for seagrass meadows.

This chapter identifies approaches for tidal wetland and seagrass ecosystem management that could contribute to carbon removal and reliable sequestration gains against the expected future baseline of natural sequestration. These include restoration of former wetlands, use of nature-based features in coastal resilience projects, managed migration as sea levels rise, augmentation of engineered projects with carbon rich materials, and management to prevent expected future losses in carbon capacity. The committee believes that implementation of these approaches could result in the storage of an additional 5.424 Gt CO_2 in coastal wetlands by 2100. Carbon sequestration is one among many ecosystem services provided by coastal wetlands that drive interest in their conservation and restoration. Ongoing restoration activities and the expected growth of coastal resilience efforts provide an opportunity to leverage carbon benefits at no or low marginal cost.

Although wetland restoration is under way is some coastal zones, uncertainty regarding its projected capacity for coastal carbon removal renders it immature as a long-term NET. Biological and geomorphic controls on the rate and permanence of carbon accumulation and sequestration are not well enough understood to predict its future impact alongside high rates of sea level rise and future coastal management practices. Significant unknowns remain about the influence of future changes in coastal watersheds on the fundamental controls on OC burial and of human interventions.

In this chapter, the committee presents a research agenda of basic research, pilot deployment, and monitoring with the aim to better understand the controls on the baseline level of carbon sequestration for the remainder of the century as well as to enhance sequestration rates above the shifting baseline. In addition, societal decisions about climate adaptation and coastal development will influence the ability to maintain or increase coastal wetland area (Schuerch et al., 2018). Therefore, the research agenda also outlines information needs regarding societal responses to land-use change in the coastal zone.

CHAPTER THREE

Terrestrial Carbon Removal and Sequestration

INTRODUCTION

Definition of Terrestrial Carbon Sequestration

Terrestrial carbon sequestration is defined here as the increase in the amount and maintenance over time of organic carbon (OC) in biological stocks, driven by plant assimilation of CO_2 from the atmosphere. Biological carbon stocks are largely controlled by actively cycling processes, that is, assimilation (carbon uptake from the atmosphere) and respiration (carbon loss to the atmosphere). The carbon stocks of interest are those that can accumulate and persist over multidecadal timescales, namely woody biomass and coarse woody debris and soil organic matter (SOM). More ephemeral carbon stocks, including herbaceous biomass and plant litter with short residence times (<1 y), are generally ignored in the context of carbon sequestration because they do not represent a persistent removal of CO_2 from the atmosphere. Harvested woody biomass used for long-lived wood products may also accumulate and persist but is also subject to release of stored carbon as product use is discontinued—unless sequestered in a landfill. While the committee recognizes that technologies to increase carbon uptake by forestry and agriculture may cause increased emissions because of decomposition and disturbance of recalcitrant carbon in soils, virtually all the data reported are for net carbon uptake, determined from stock changes over time. Hence decomposition and disturbance impacts on carbon losses are included in the net values.

As a general principle, the overall balance of these carbon stocks is driven by the difference between carbon inputs (via plant CO_2 assimilation) and carbon losses to the atmosphere (via decomposition/microbial respiration as well as from fire/combustion). Thus, the standing stocks of carbon can be increased by increasing the rate of input of carbon, decreasing outputs of carbon, or both. For woody biomass, this implies growing more trees with more biomass per unit area, and maintaining that biomass over a longer time span, and/or decreasing loss of woody biomass through tree mortality, fire, and harvesting operations. For soil OC, this means increasing the rate of input of plant-derived detritus to the soil and/or reducing the rate at which the organic compounds added or already in the soil decompose and mineralize to CO_2. Achieving and maintaining increases in biological carbon storage requires active management practices that manipulate system carbon balances, for which a variety of existing as well as potential future options exist.

Rationale for Terrestrial Carbon Sequestration

Global terrestrial biotic carbon stocks include ca. 600 Gt C in biomass and ca. 1,500 Gt C in soil to a depth of 1 m (ca. 2,600 Gt C to 2 m); annual fluxes from and to the atmosphere and terrestrial ecosystems, on the order of 60 Gt C yr^{-1}, are roughly balanced but with an average net residual carbon uptake by terrestrial ecosystems of 1-2 Gt C (Le Quéré et al., 2016). However, historically the conversion of native ecosystems to managed land, particularly cropland, has been a large net source of CO_2 flux to the atmosphere with a significant depletion of biomass and soil carbon stocks, particularly over the past ca. 200-300 years as human population and land transformation exploded. Recent estimates of the anthropogenic-induced losses of terrestrial carbon stocks are on the order of 145 Gt C from woody biomass and soils from 1850 to 2015 (Houghton and Nassikas, 2017), 133 Gt C from soil carbon stocks over the past 12,000 years (Sanderman et al., 2017), and 379 Gt C of biomass over the past 10,000 years (Pan et al., 2013). These estimates of historical losses indicate a hypothetical though highly impractical upper bound for restoring terrestrial carbon stocks through adjustments to land management.

The rationale for pursuing terrestrial carbon sequestration as a CO_2 removal strategy is at least three-fold. First, the "technology" for carbon capture and storage already exists, via the uptake of CO_2 by plants and its storage in longer-lived biotic carbon pools, providing opportunity for storage that is energetically and economically competitive with other carbon removal and mitigation options. Second, there is a significant storage capacity based on the magnitude of historical carbon stocks compared with much lower contemporary stocks. To a large extent, terrestrial carbon sequestration approaches can be seen as a reversal of previous ecosystem degradation—changing land use and management to favor greater biomass and soil carbon stocks. Third, increasing biomass and soil carbon stocks may confer additional ecosystem service benefits, including watershed protection, increased biodiversity, and improved soil health and fertility. In contrast, ecosystem service benefits, including biodiversity, may be reduced if the carbon sink–creating activities change disturbance regimes or other landscape characteristics that affect species. These are discussed in more detail below.

APPROACHES FOR TERRESTRIAL SEQUESTRATION

The committee's assessment of terrestrial carbon sequestration options centers around the predominant types of managed ecosystems: forestland, cropland, and grassland, each with multiple management "levers" to modify carbon stocks. Other intensively managed land such as urban/peri-urban landscapes contain biotic carbon stocks in trees and greenspaces (e.g., parks, lawns), for which some of the sequestration practices described under the forestland and grassland category could apply. Wetlands are of particular importance because they contain the highest carbon stocks per unit area of any ecosystem. Where they have been drained and converted to crop, grazing, or forest production, approaches to recover carbon sequestration capacity will be discussed under each of the three main land-use types. Coastal ecosystems (i.e., "coastal blue carbon"), which exist on the edge of terrestrial and ocean ecosystems, are covered in Chapter 2. Bioenergy with carbon capture and storage (BECCS) is likewise covered in Chapter 4, with references to this chapter regarding land requirements for all approaches.

In describing technical options, the committee distinguishes between "conventional" and "frontier" technologies or practices to increase carbon stocks via CO_2 removals. Conventional practices refer to management practices that are already in use, to a limited degree, and have an existing body of applied research knowledge. Increasing carbon stocks via these practices mainly requires a much greater degree of participation by land managers and refinement in their applicability and support services to facilitate broader adoption. In contrast, frontier technologies are still in the basic research phase and have not been tested for widespread deployment (e.g., perennial grain crops) or involve practices (e.g., "enhanced wood preservation") that fall outside the framework of current land management practices.

Conventional Forest Practices

Forestry practices that can act to remove CO_2 and reduce emissions fall into three categories of action: (1) avoiding conversion of forest land to other land uses (deforestation) that store less carbon and have lower rates of removal, (2) converting non-forest land to forest (afforestation/reforestation) thereby increasing carbon removal and stocks, and (3) modifying forest management practices to either increase carbon stocks or increase net removals from the atmosphere (balance of gains and losses of CO_2), or both. Modifying forest management involves an array of practices, such as accelerated regeneration of nonstocked forest after disturbance, which increases carbon removal in the near term; restoring degraded forests to healthier and sustainable conditions that maintain removal capacity, and extending the rotation length (age of forest at harvest); which maintains removal capacity, avoids emissions associated with wood harvest, and directs more biomass into long-lived wood products that store harvested carbon. Altering management and wood product design to foster preservation of more long-lived wood products that store the harvested biomass carbon is a fourth category that is treated later in this chapter as a frontier technology.

Assessment of the carbon consequences of forestry activities is complicated by the many different direct and indirect effects on the carbon cycle. Forest ecosystems are composed of three main carbon pools that respond differently to harvesting, management, and other disturbances: live biomass (above- and below-ground); standing and down dead wood; and SOM including surface litter, humus, and mineral soil layers. These carbon pools respond to disturbances over periods of years to decades such that accounting for impacts is an ongoing process. Besides ecosystem impacts, harvested wood products have multiple effects on the carbon cycle including their function as temporary storage of removed carbon while in use or disposal, substitution of wood for other construction materials that require substantial quantities of fossil energy to produce (avoided emissions), and use of wood for biofuel, which may reduce net emissions relative to burning fossil fuels (discussed in Chapter 4).

Although avoiding deforestation typically has the most significant and immediate impact on a per-hectare (ha) basis by reducing emissions and sink capacity, it is not explored in depth in this report because it is mainly an emissions reduction or avoidance activity rather than an activity that increases CO_2 removal. Avoiding deforestation is a potentially significant activity, with avoided emissions ranging from 56 to 116 Mg C/ha/y in the United States and 96-103 Mg C/ha/y globally (EPA, 2005; Griscom et al., 2017).

Afforestation/Reforestation

Afforestation/reforestation has been extensively studied and implemented in the United States and around the world, so may be considered immediately deployable for carbon removal purposes. Afforestation/reforestation involves planting trees or facilitating natural regeneration of trees on land that has been in a nonforest use condition for some length of time. The committee considers regeneration of a harvested forest as a forest management practice even though tree cover may have been *temporarily* reduced to a level typical of nonforest use. Foresters have planted new forests or reforested nonforest lands for many decades and have good knowledge of which species are likely to be successfully established and which areas are suitable for planting or assisted natural regeneration (Sample, 2017). In regions where tree planting is associated with timber production, such as the U.S. Southeast and Pacific Northwest, provenance trials, tree breeding programs, and genetic improvements have progressed to identify trees that have good survival rates, grow fast, and have properties that are most suitable for wood products (Burley, 1980). However, to date, carbon removal rates have not been the target of research about growing stock improvements; instead, improvements in planting stock have been targeted to increase timber production (above-ground biomass) while the effects on below-ground biomass and soil carbon remain largely unknown (Noormets et al., 2015). As a result, there is a need to consider selections of trees that would increase whole-tree biomass as a means to increase their function as carbon removal organisms (e.g., Muchero et al., 2013). Data on tree growth and carbon removal rates are readily available, as are guidelines for successful planting and natural regeneration. Table 3.1 illustrates some of the more common and representative carbon removal rates that span a wide range of values because of heterogeneous climates, sites, and forest types.

Rates of ecosystem carbon increase with afforestation/reforestation in the United States range from 0.7 to 6.4 Mg/ha/y for a period of 50-100 years or more (Table 3.1). The carbon removal rate is variable over this time period, generally following a growth

TABLE 3.1 Published Estimates of Biomass Carbon Sequestration Rates for Various Forestry Activities

Global Estimates		
Activity	**Net stock increase (Mg/(ha y) C)**	**Reference**
Afforestation/Reforestation	2.8-5.5	Griscom et al., 2017
Afforestation/Reforestation	3.4	Smith et al. 2016
Improved forest management	0.2-1.2	Griscom et al., 2017
U.S. Estimates		
Activity	**Net stock increase (Mg/(ha y) C)**	**Reference**
Afforestation/Reforestation	0.7-6.4	Birdsey, 1996
Improved forest management	1.4-2.5	Denef et al., 2011

curve with a diminishing rate of increase as the forest reaches maturity (Figure 3.1). However, if the activity is initiated over a period of years on different parts of the landscape, which would be likely given infrastructure and funding constraints, the idealized pattern of incremental carbon storage may be more linear except for the early years (Figure 3.2). Estimates of the potential carbon sink from afforestation/reforestation include changes in biomass and soil carbon without consideration of impacts of future harvesting or natural disturbances. Disturbances would release stored carbon from the ecosystem. In the case of harvesting, some of the carbon lost from the ecosystem would be retained in wood products or landfills. Increases in harvested wood products may also reduce emissions through substitution of wood for other types of construction materials that require more energy to produce. Emissions reductions from increasing harvested wood in place of other materials are not estimated here even though potentially significant, because these activities do not represent increases in carbon removal.

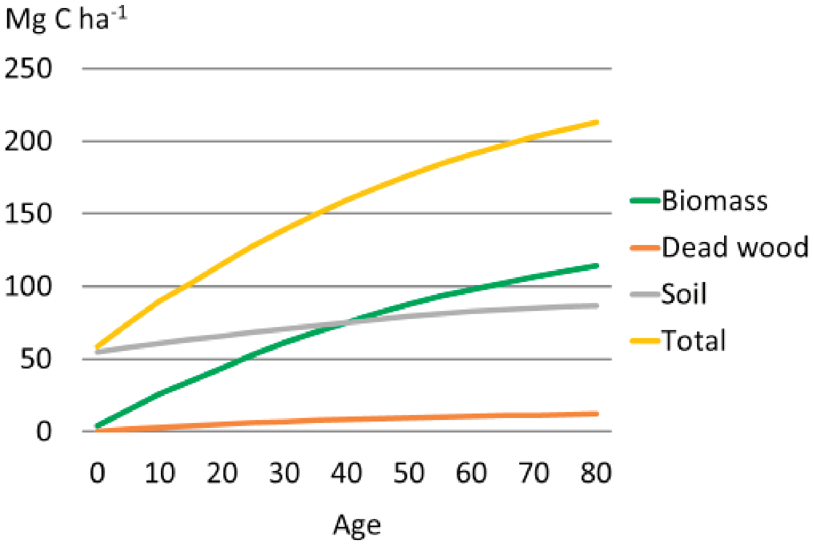

FIGURE 3.1 Changes in carbon stock from afforestation.
NOTE: Example is for loblolly-shortleaf pine in the Southeast United States. SOURCE: Data from Smith et al., 2006.

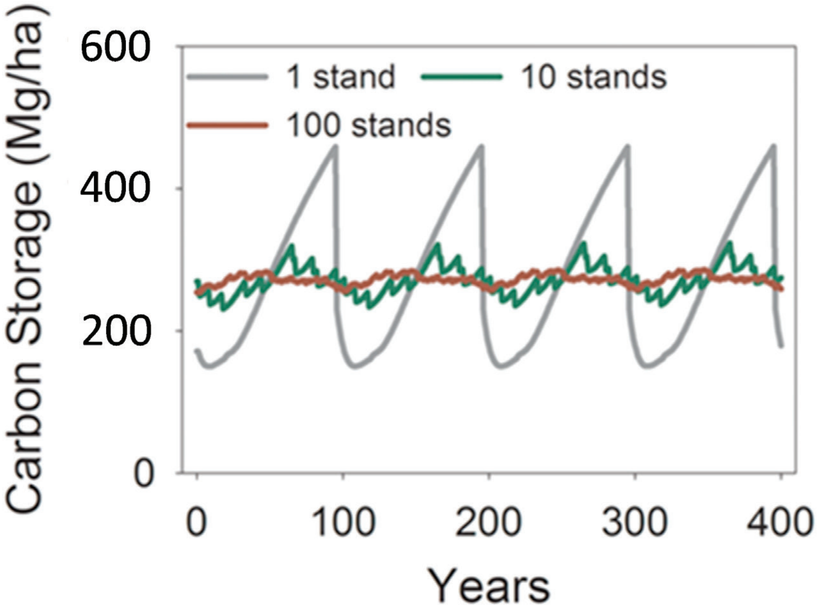

FIGURE 3.2 The impacts of management actions on carbon storage of a hypothetical Douglas fir forest at different spatial scales. SOURCE: Adapted from McKinley et al., 2011.

Improved Forest Management

Improved forest management has been extensively studied in developed countries with respect to impacts on carbon removal, feasibility, and cost; therefore, this technology may be considered as immediately deployable. Forest management involves a very wide array of practices that have been tailored for regional and local conditions based on experience and extensive silvicultural experiments, many of which have been ongoing for decades (Malmsheimer et al., 2011; McKinley et al., 2011). In general, promising forest management practices to increase carbon removal include the following:

- Accelerating regeneration in areas that have had major disturbances;
- Restoring forests that have been converted to "unsustainable" forest conditions, which includes both increasing carbon stocks by returning a forest to its original vegetation type that is better adapted to site and climate, and reducing carbon stocks of overstocked stands to levels that are less likely to have intense wildfires that convert the forest to the much lower carbon density of nonforest;
- Extending harvest rotations to grow larger trees and sustain carbon removal rates (not to mention avoid emissions associated with harvest);

- Maintaining healthy forests by treating areas affected by insects and diseases or preventing conditions that foster outbreaks; and
- Thinning and other silvicultural treatments that promote overall higher stand growth compared with untreated conditions.

Changing forest management practices such as extending timber harvest rotations and improving stocking and productivity could store an additional 0.2 to 2.5 Mg C/ha/y for several decades based on U.S. and global estimates (Table 3.1). These estimates include changes in biomass and soil carbon but exclude changes in the stock of harvested wood products. Emissions reductions from increased use of harvested wood in place of other materials are not estimated here even though potentially significant, because these activities do not represent increases in carbon removal.

The range of potential benefits from improved forest management is very wide because of the need to account for different land use and management histories as well as the many different climates, site conditions, and forest types. Generally, the per-hectare values are significantly less than observed for afforestation/reforestation because the growing stock of trees in an existing forest in the absence of management will still take up significant quantities of CO_2; therefore, the additional uptake of CO_2 is less than if comparing forest with no forest (McKinley et al., 2011).

Frontier Forest Practices

Increase Harvested Wood Use and Preservation

According to many studies, the main climate benefit of increasing the use of harvested wood products is emissions reductions from the substitution of wood products for materials such as concrete and steel that require more fossil fuels for production (e.g., Hashimoto et al., 2002; Perez-Garcia et al., 2005; Sathre and O'Connor, 2010). However, increasing the preservation of harvested wood by improving preservative treatment methods (Song et al., 2018) or advanced landfilling could be a significant CO_2 removal approach with additional economic benefits. Zeng (2008) proposed harvesting live trees and other biomass from managed forests and burying the logs in trenches or otherwise storing them to prevent the carbon from being released. Improving the preservation of wood products from existing harvest operations and potentially increasing harvest with high levels of product preservation could be viable approaches to increasing carbon removal.

Wood removals from the world's 4 billion ha of forests average around 3 billion m^3/y or 0.65 percent of the growing stock, of which about half is for timber products and half for fuel (FAO, 2015b). During harvest, a significant portion of the live biomass is left in the forest as logging slash (not including tree roots), ranging from roughly 30-40 percent of the pre-harvest biomass at the national scale, with much higher variability at more local scales (Oswalt et al., 2014; Winjum et al., 1998). Some of this logging slash is used for fuelwood and charcoal. Much of industrial wood removals comes from approximately one-half of the world's forests designated for timber production or multiple use (FAO, 2015b).

Much of the biomass removed from forests for timber products is emitted during primary processing into products, with losses ranging from roughly 20 percent to 60 percent depending on conversion efficiency (Bergman and Bowe, 2008; Ingerson, 2009; Kline, 2005; Liski et al., 2001). After the end of their useful life, wood products are typically deposited in landfills that are often designed for relatively rapid decomposition, or subject to other fates such as deposit in dumps that emit their stored carbon (Skog, 2008). According to several estimates, about 0.5 to 0.7 Gt/y CO_2 of the harvested carbon is sequestered in use or landfills after accounting for the inputs from current harvests and inherited losses from past harvests (Hashimoto et al., 2002; Miner and Perez-Garcia, 2007; Pan et al., 2011; Winjum et al., 1998).

Conventional Cropland and Grassland Practices

The vast majority of agricultural lands around the world are not managed optimally for increased soil carbon storage. Most annual croplands in temperate climates have bare-fallow conditions outside of the main crop-growing season, and intensive tillage practices are still widespread. Some annual cropland is on marginal lands that are subject to continuing soil degradation. Many pastures and rangelands employ unimproved grazing systems and suboptimal forage management. However, numerous conservation management practices are available that can increase carbon stocks in soils and are successfully practiced by progressive farmers and ranchers. In many cases these practices have been well studied, with long-term field experiments and comparative field observations. Table 3.2 lists several categories of management practices, classified according to their main mode of action in either increasing carbon inputs to soils and/or reducing carbon losses from soils.

Following implementation of improved practices, soil carbon accrual rates can continue over several decades but attenuate over time as soil carbon contents tend toward a new equilibrium state with no further carbon gains unless additional carbon-accruing management practices are adopted. Furthermore, because of the dynamics of mineral-organic matter interactions that largely control the residence time of

TABLE 3.2 Examples of Conventional Agricultural Management Actions That Can Increase Organic Carbon Storage and Promote a Net Removal of CO_2 from the Atmosphere

Management Practice	Increased carbon inputs	Reduced carbon losses
Increased productivity and residue retention	X	
Cover crops	X	
No-tillage and other conservation tillage	X	X
Manure and compost addition	X	
Conversion to perennial grasses and legumes	X	X
Agroforestry	X	X
Rewetting organic (i.e., peat and muck) soils		X
Improved grazing land management	X	X

SOURCE: Adapted from Paustian, 2014.

carbon in soil (Lehmann and Kleber, 2015), soils with initially low carbon concentrations have a greater propensity to gain carbon compared to soils with already high carbon concentrations. Thus there is effectively a "saturation limitation," which varies as a function of soil texture and mineralogy (Stewart et al., 2007) and hinders further carbon accrual for mineral soils with very high organic matter contents.

Improved Annual Cropping Systems

On annual croplands, farmers may adopt several cropping choices that increase inputs of carbon into soils: replacing winter bare-fallow with seasonal cover crops, planting crops that produce large amounts of residues, promoting more continuous cropping (reduced summer fallow frequency) in semi-arid environments, and increasing the proportion of perennial grass/legume forage crops within crop rotations. Such cropping choices can maximize the time during which live vegetated cover is maintained on the soil and increase the amount of root-derived carbon added to the soil (Rasse et al., 2005). In the past few years, interest has grown in the use of cover crops, which have been strongly promoted by the U.S. Department of Agriculture's (USDA's) Natural Resource Conservation Service. Cover crop adoption is rising; however, adoption rates in the United States remain low (<5 percent of cropland area; USDA, 2014). This reflects unfamiliarity for growers, barriers from additional costs, restrictions related to crop insurance, and possibly immature technology in some areas. Systems to increase cropping frequency and reduce summer-fallow in semi-arid cropland have been successful in increasing productivity as well as soil carbon stocks (Peterson et al., 1998), although large areas dominated by alternate year wheat summer-fallow practices remain. Wider adoption of crop rotations that incorporate 2 to 3 years of grass or legume hay with annual crops (common in mid-20th century Corn Belt agriculture) is limited by the higher prices for main commodity crops (e.g., corn, soybean), which encourages continuous grain mono-cropping. Hence, for a variety of reasons, best cropping practices for sequestering carbon are not widely used on U.S. annual cropland, which means there is ample room to increase adoption rates if soil carbon sequestration becomes a more prominent policy goal.

Farmers use tillage to manage crop residues and prepare a seed bed for crops, and it is the main source of soil disturbance in croplands. Intensive tillage tends to accelerate decomposition rates of SOM (Paustian et al., 2000). Advances in tillage implement technology and agronomic practice have allowed farmers in recent decades to reduce tillage frequency and intensity, sometimes ceasing tillage altogether with a practice known as "no-till." Reduced tillage systems, particularly no-till, can increase the mean residence time and slow decay of SOM (Six and Paustian, 2014), promoting greater soil carbon storage (Table 3.3). Many field studies show increases in soil OC following adoption of reduced till and no-till, with variations due to soil texture and climate. However, there are instances in which no-tillage does not increase soil carbon relative to conventional tillage, particularly in wet, cool climates where productivity under no-till may be reduced (Ogle et al., 2012) and in soils with already high topsoil carbon contents, where organic matter stabilization efficiency may be lower than for residues mixed deeper into the soil with tillage (Angers and Eriksen-Hamel, 2008; Ogle et al., 2012). No-till and reduced tillage are not widely adopted on most annual cropland in the United States, although there is significant regional variation.

In summary, a combination of an extended vegetated period, increased residue (particularly root-derived) inputs, and minimal tillage systems could be broadly implemented as best practices for increasing soil carbon stocks on annual cropland. Rates vary significantly as a function of climate, soil, and land-use history, but rates of 0.2-0.5 tC/ha/y over time periods of 20-40 years are representative, as observed in numerous meta-analyses of long-term field experiment data both globally and in the United States (Table 3.3).

TABLE 3.3 Examples of Published Summaries and Meta-Analyses for Soil Carbon Sequestration Rates with Conservation Practice Adoption on Annual Cropland

Practice(s) adopted	Δ SOC (SE) (t/(ha y))	Region	# of field comparisons	Source
Crop rotation				
Cover crop	0.32 (0.08)	Global	139	Poeplau and Don, 2014
Cover crops	0.36	US	31	Eagle et al., 2012
Improved rotations	0.14-0.18[a]	US	78	Eagle et al., 2012
Improved rotations	0.1-0.21[b]	Global (Temperate-dry)	13	Ogle et al., 2005
Improved rotations	0.17-0.34[b]	Global (Temperate-moist)	13	Ogle et al., 2005
Conservation tillage				
No-till	0.48 (0.13)	Global	276	West and Post, 2002
No-till	0.15-0.80[b]	Global	160	Ogle et al., 2005
No-till	0.33	US	282	Eagle et al., 2012
No-till	0.30 (0.05)	Southeast US	60	Franzluebbers, 2010
No-till + cover crops	0.55 (0.06)	Southeast US	87	Franzluebbers, 2010
No-till	0.48 (0.59)	Northcentral US	19	Johnson et al., 2005
No-till	0.27 (0.19)	Northwest US	40	Liebig et al., 2005

[a] Range in mean values is for rotation improvements from elimination of bare (summer) fallow and adding perennials forages (for 1-3 years) to annual crop rotations.

[b] These studies reported annual changes in SOC stock (0-30 cm depth) as percentage changes relative to baseline soil carbon stocks. To convert to an amount (t/ha/y) for a representative range of SOC change rates, the committee used 15 tC/ha and 60 tC/ha (0-30 cm depth) as high and low stock values, respectively. These correspond to low and high values for carbon stocks on permanent cropland amount major soil classes in the Intergovernmental Panel on Climate Change (IPCC) soil carbon inventory methodology (IPCC, 2006).

NOTE: Delta SOC denotes mean change in soil OC stocks (t C/ha/y) with standard error (SE) (where reported), or in some cases values are reported as a representative range in mean annual change rates.

Organic Matter Amendment

Organic matter additions such as animal manures and composts can increase soil carbon contents, both by virtue of the added carbon in the amendment itself and through improving soil physical attributes and nutrient availability. Cropland soils receiving substantial organic amendments invariably show increases in soil carbon concentrations derived from the amendment itself. However, this does not equate necessarily with a CO_2 removal from the atmosphere, but simply a transfer of carbon from another location (Leifeld et al., 2013). To the extent that the amendments improve soil performance and thus increase in situ plant productivity and residue carbon inputs, then the amendment can in fact stimulate real increased CO_2 removals. Hence a full life cycle assessment (LCA) approach in which the boundaries of the assessment extend outside the farm to include the greenhouse gas (GHG) and net carbon emissions with the production and baseline utilization of the amendment is needed for an accurate accounting of net CO_2 impacts. Because nearly all raw animal manure is land applied (Wu et al., 2013), increasing rates of manure addition at one location would necessitate an equal reduction elsewhere. Hence, counting the manure carbon added as part of the overall carbon balance is problematic. For other waste streams, such as municipally sourced compost, where the alternative use may be landfilling, an LCA approach that accounts for net emissions associated with a landfilling alternative vs production and land application of compost could be evaluated as a CO_2 emission strategy. One study of compost applications to grasslands in California (DeLonge et al., 2013; Ryals and Silver, 2013) estimated a net CO_2 removal and GHG reduction of 23 tCO_2e/ha for the first 3 years following compost application, because of soil carbon increase (discounting added compost carbon) and net avoided GHG emissions from diverting lagoon-stored manure and landfilled green waste to compost. However, similar studies are lacking for other areas in the United States.

Conversion of Annual Cropland to Perennial Vegetation

Probably the most effective means of increasing soil carbon stocks on annual cropland is to convert to perennial vegetation, either for grazing and forage production, afforestation (see previous section), dedicated energy crops (e.g., switchgrass, miscanthus), or as conservation set-aside. Perennial grasses in particular allocate a large fraction of their carbon assimilates to below-ground production, which enter the SOM pool through root exudation, sloughing, and turnover. Over time, in the absence of long-term soil degradation, SOC stocks can approach or equal those in precultivation native grassland systems. Perennial grasses purposed as dedicated energy crops (see Chapter 4) and established on former cropland typically increase soil carbon stocks, which can contribute to the net GHG balance of those systems (Field et al., 2018; Liebig et al., 2008). Conversion to perennial woody vegetation (e.g., forest) increases stocks of woody biomass carbon but may also increase soil carbon stocks. In many cases, accrual rates are similar to those for conversion to grassland vegetation (Guo and Gifford, 2002; Post and Kwon, 2000), although some studies suggest that soil carbon gains occur under deciduous species whereas soil carbon gains under coniferous woody vegetation are minimal (Laganière et al., 2010; Morris et al., 2007). Several meta-analyses have documented soil carbon gains on cropland converted to perennial vegetation (Table 3.4).

TABLE 3.4 Examples of Published Summaries and Meta-Analyses for Soil Carbon Sequestration Rates Following Conversion of Annual Cropland to Perennial Grassland or Forest Vegetation

Practice(s) adopted	**Δ SOC (SE) (t C ha/y)**	**Region**	**# of field comparisons**	**Source**
Annual cropland to grassland	0.9 (0.1)	Global	161	Conant et al., 2017
	0.12-1.1[a]	Global	58	Ogle et al., 2005
	0.28-0.56	Global	76	Guo and Gifford, 2002
	0.33	Global	46	Post and Kwon, 2000
Annual cropland to forest	0.27-0.54	Global	38	Guo and Gifford, 2002
	0.34	Global	30	Post and Kwon, 2000
	0.16-1[a]	Global	189	Laganière et al., 2010

[a] These studies reported annual changes in SOC stock (0-30 cm depth) as percentage changes relative to baseline soil carbon stocks. To convert to an amount (t/ha/y) for a representative range of SOC change rates, we used 15 tC/ha and 60 tC/ha (0-30 cm depth) as high and low stock values, respectively. These correspond to low and high values for carbon stocks on permanent cropland amount major soil classes in the IPCC soil carbon inventory methodology (IPCC, 2006).

NOTE: Delta SOC denotes mean change in soil OC stocks (tonnes C/ha/y) with standard error (SE) (where reported), or in some cases values are reported as a representative range in mean annual change rates.

Agroforestry

Agroforestry involves the incorporation of trees into agricultural systems, either in combination with annual crops or grazed pastures (the later often referred to as silvopastoral systems). There are many different practices in which trees may be interspersed with crops (e.g., alley cropping) or herbaceous forage, used as border or buffer plantings (e.g., living fences, windbreaks, forest buffers) or used in a time sequence or rotation with annual crops (e.g., improved tree fallows). Regardless of form, the inclusion of perennial woody species in combination with annual crops or pastures typically results in increased soil carbon stocks and woody biomass stocks (Table 3.5).

Improved Grazing Land Management

Grasslands contain some of the highest soil carbon stocks of any managed ecosystems. With the exception of some managed pastures, grazing lands are infrequently or never tilled, and the perennial grasses that dominate in most rangelands and pasture allocate a substantial portion of their photosynthetically fixed carbon below ground, thus supporting comparatively large soil carbon stocks.

Grasslands in the United States can be loosely categorized into *pastures*, which are typically in more mesic (i.e., moister) environments, with higher productivity, often with selected (sown) species and more intensive soil management such as fertilization, liming, and irrigation. Pastures in some cases may be rotated with annual crops

TABLE 3.5 Examples of Carbon Accrual Rates for Biomass and Soil Carbon from Recent Meta-Analyses and Multisite Assessments of Temperate Zone Agroforestry Practices

Practice(s) adopted	**Δ C stock (t ha/hr)**	**Years**	**Region**	**# of Field Comparisons**	**Source**
Alley cropping (wood carbon)	0.65	6-41	France	13	Cardinael et al., 2017
Alley cropping (soil carbon)	0.24	6-41	France	6	Cardinael et al., 2017
Agroforestry (soil carbon)	0.43-1.88	NR	US	NR	Eagle et al., 2012

NOTES: Delta carbon denotes mean change in soil OC or biomass stocks (tonnes C/ha/y), or in some cases values are reported as a representative range in mean annual change rates. NR denotes not reported.

and typically have soils that were tilled at some time in the past. In contrast, *rangelands* are mainly found in semi-arid and arid climates, are usually dominated by native grassland vegetation, often have never been tilled, and usually have no (or minimal) management interventions in terms of fertilizer or irrigation use. Grazing management is the primary management "lever" for rangelands.

Grazing management influences grassland productivity and carbon storage (Table 3.6) in both pastures and rangelands, via the amount, timing, and duration of vegetation removal by grazing animals (Milchunas and Lauenroth, 1993). With excessive grazing pressure (overgrazing), plant productivity and hence carbon uptake is reduced and soil carbon stocks decrease (Dlamini et al., 2016). Therefore, reducing stocking rates and grazing intensity can allow vegetation productivity to recover and carbon stocks to increase. However, other than eliminating overgrazing, there is considerable debate regarding the impact on soil carbon of more intensively managed grazing systems (i.e., rotational grazing, adaptive multipaddock, mob grazing), compared with less intensively managed, continuous grazing systems. It has been suggested that management-intensive grazing—short heavy-grazing periods followed by long grazing-free periods—can increase soil carbon storage (Chaplot et al., 2016; Wang et al., 2015), although many experiments do not show a significant difference between light to moderate continuous grazing vs management-intensive grazing (Briske et al.,

TABLE 3.6 Examples of Soil Carbon Sequestration Rates from Recent Meta-Analyses and Field Studies of Improved Grassland Management Practices

Practice(s) adopted	Δ SOC (SE) (t C ha/y)	Region	# of field comparisons	Source
Improved fertility	0.57 (0.08)	Global	108	Conant et al., 2017
Legume inter-seeding	0.68 (0.22)	Global	13	Conant et al., 2017
Improved grazing	0.3 (0.14)	Global	89	Conant et al., 2017
Improved grazing	-0.8 to +1.3	US	13	Eagle et al., 2012
Adaptive multipaddock	0.48	US (Texas)	6	Teague et al., 2011

NOTE: Delta SOC denotes mean change in soil OC stocks (tonnes C/ha/y) with standard error (SE) (where reported), or in some cases values are reported as a representative range in mean annual change rates.

2008). However, the interactions that determine vegetation productivity and soil carbon responses for different grazing systems are complex (McSherry and Ritchie, 2013). In general, grazing systems that maintain plant cover and maximize plant vigor and productivity are most conducive for building and maintaining soil carbon stocks (Eyles et al., 2015). Additional field-based research and improved models are needed to determine the best grassland- and region-specific systems for promoting soil carbon sequestration and their capacity for net GHG reductions and CO_2 removal (Conant et al., 2017; Eyles et al., 2015).

Rewetting of Organic Soils

Organic soils (i.e., peat and muck soils), which develop under wetland vegetation and are saturated with water to the soil surface for a substantial part of the year, have extremely high organic matter content (>12 percent of soil mass as OC, for a minimum 20 cm horizon depth; FAO, 1998) that can extend to several meters in depth. When converted to agricultural use (or forest plantations) following drainage, liming, and fertilization, they can be extremely productive soils, but with rapid rates of organic matter decomposition and carbon loss rates as high as 20 tC ha/y (Armentano and Menges, 1986). Consequently, restoring the wetland hydrology and perennial vegetation can reverse the processes driving soil carbon losses and greatly reduce CO_2 losses compared to drained organic soils and in many cases can reestablish the soil as a net carbon sink, although increased methane (CH_4) emissions following rewetting can decrease the overall net sink. In a global review, Wilson et al. (2016) reported that rewetting managed organic soils led to net annual CO_2 removals for most soil classes (usually <1 tC ha/y), varying as a function of thermal regime, site productivity, water table height, and time since restoration. Most lacking are data for impacts of restoration on tropical organic soils.

Frontier Cropland and Grassland Practices

The management interventions described above are well known and used to varying degrees in the United States and elsewhere and have been the subject of previous (and ongoing) research. In most cases, causal mechanisms and relative magnitude of carbon stock responses are known, although important basic and applied science questions remain. In contrast, the committee characterizes several approaches as "frontier technologies" because they are in an early stage of development; many questions regarding rates and capacities for carbon removals remain unanswered, and there has been little or no deployment of these technologies outside of field research situations. Two of the technologies involve increasing the residence time and stability of OC in soils, and the other two involve developing plants with greatly enhanced capacity to add carbon to the soil.

Biochar Amendment

Pyrolysis (heating in the absence of oxygen) of plant material is an exothermic (i.e., energy-yielding) process that produces volatile compounds and oils (which can be purposed for bioenergy and biomaterials), as well as solid, "charred" organic residues with high aromaticity and reduced O:C and H:C ratios, that are much more resistant to microbial decomposition than the original plant residues (e.g., straw, wood, shells). The longevity of biochar applied to soil can vary substantially depending on the pyrolysis temperature and duration, biomass type, and climate and soil conditions. Highly condensed, low H:C chars derived from wood are highly recalcitrant and can remain in soils over century timescales (Lehman et al., 2015). Naturally occurring pyrogenic carbon (e.g., black carbon, charcoal) comprises a substantial portion of the total soil OC in many fire-prone grassland and forest ecosystems (Skjemstad et al., 2002), and additions of charred biomass by Neolithic farmers have resulted in soils with greatly increased OC stocks (e.g., *Terra Preta* soils of the Amazon; Glaser and Birk, 2012).

Pyrolysis is a bioenergy pathway (predominantly for the production of liquid biofuels) that could be part of a bioenergy production strategy (see Chapter 4). Pyrolysis BECCS aims to both displace fossil-based fuels as well as produce a biochar coproduct that can be added to soils for long-term carbon storage. Alternatively, purposed biochar production, with the pyrolysis liquids and volatiles combusted for process heat and/or energy generation, can produce biochar as the main product for soil application to sequester carbon and improve agronomic performance. The extent to which biochar production and addition to soil represents a net CO_2 removal depends on a full life-cycle consideration of all GHG emissions associated with the biomass sourcing, its production and use, and fossil fuel offset values (Roberts et al., 2010; Woolf et al., 2010). In addition, indirect impacts of soil application of biochar on other biogenic GHG emissions and plant carbon uptake factor into assessments of its potential to reduce net GHGs. Recent meta-analyses suggest that biochar applications may reduce nitrous oxide (N_2O) emissions from soil on the order of 10 percent (Verhoeven et al., 2017), although the response varies between soils, with some biochar additions increasing N_2O flux. Sánchez-García et al. (2014) suggest that biochar decreases N_2O emissions from the denitrification (anaerobic) pathway but increases emissions from the nitrification (aerobic) pathway, possibly accounting for some of the differences between soil types and soil conditions in biochar effects on N_2O flux. Biochar applications also appear to decrease CH_4 emissions from flooded (e.g., rice) soils and in acid soils (Jeffery et al., 2016), whereas application to nonflooded soils with neutral or alkaline pH may reduce rates of CH_4 oxidation (a CH_4 sink). Finally, biochar application often increases plant productivity and hence plant carbon inputs to soil, particularly in highly weathered and acidic soils, averaging about a 10 percent increase in recent meta-analyses (Jeffery et al., 2011; Verhoeven et al., 2017). However, plant responses vary by soil type, biochar attributes, and management systems, and thus further research is needed to better identify conditions under which biochars can best increase plant carbon uptake, reduce non-CO_2 GHG emissions, and contribute to net CO_2 removals from the atmosphere.

Deep Soil Inversion

Placing organic matter–rich surface soil into subsoil layers, through a one-time deep inversion tillage, may substantially increase the overall SOM residence time. For most soils, microbial activities decrease sharply with depth, because of less aeration, cooler temperatures, and sparser and more dispersed organic matter inputs. In addition, the placement of low organic matter content subsoil at the top of the soil profile where the majority of the root system resides will increase soil carbon sink generated by root system and photosynthesis process. Alcantara et al., 2016 found that deep plowing and burial (to >50 cm depth) of organic matter–rich surface soil horizons, coupled with subsequent enhanced carbon accumulation in surface-exposed and carbon-depleted subsoil horizons, yielded an average carbon accumulation rate of ca. 3.6 tCO_2 ha/y over a 40-year time period at several cropland sites in Germany. Testing of deep inversion tillage for carbon storage has recently started in some other locations (e.g., New Zealand; M. Beare personal communication), but not to the committee's knowledge in the United States. A large portion of U.S. cropland in humid regions, particularly in the Central and North-Central states, might be potential areas for implementation.

High Carbon Input Crop Phenotypes

The most direct way to increase soil carbon storage is to increase the rate of OC addition to soils in the form of plant residues, particularly below ground. Here we discuss two approaches: (1) increasing the relative amount of carbon allocated to roots for the annual crops that dominate current agricultural food production systems and (2) developing new perennial food crop species, which have inherently higher below-ground carbon allocation and could mimic the high soil carbon storage capacity found in perennial pasture grasses.

Breeding for Annual Crops with Increased Carbon Input

A main reason that annual crops are less effective at increasing soil OC stocks compared to perennial grasses is the smaller amount of dry matter allocation below ground to roots and rhizosphere deposition. Most soil OC is derived from roots (as exudates and through root death and turnover; Rasse et al., 2005), and thus an option to increase soil OC stocks would be to develop crops that allocate more dry matter below ground and/or have deeper root systems where the decomposing OC compounds would have a longer mean residence time (Kell, 2012). Increasing carbon allocation to roots without reducing above-ground yields will be a key issue for crop breeders, but is possible for several reasons. Many root characteristics (e.g., architecture, depth distribution, size) are strongly controlled by genetic traits that can be selected for (Hochholdinger et al., 2004; York et al., 2015). Where available nutrients such as phosphorus limit yields (common in tropical soils), enhanced root growth can increase nutrient acquisition and increase total assimilation and yield (Lynch, 1995). Finally, sink size inhibition often limits total plant carbon assimilation and thus plant breeding because an increased root carbon sink does not necessarily reduce above-ground productivity and yields (Jansson et al., 2010). Preliminary estimates suggest that widespread adoption of annual crops with enhanced root-phenotypes could increase carbon stocks in U.S. soils by 500-800 Mt/y CO_2e over several decades (see Table 3.7).

Perennializing Grain and Oilseed Crops

The dominant commodity crops in the world are grains (e.g., maize, wheat, rice, sorghum, millet) and oilseeds (e.g., soybean, pulses, sunflower), which must be replanted each year and have been bred to maximize dry matter allocation to the harvested seed. Compared to perennial grasses and forbs, current varieties for these annual crops allocate much less carbon to roots and unharvested residues and are less effective at building and maintaining high soil carbon stocks. Thus, developing seed crops with a perennial growth habit and greater below-ground carbon partitioning could radically increase the potential for soil carbon gains, if perennialized crops could substitute for a substantial portion of current production from annual crops.

Research to develop perennial analogs for major annual crops commenced only within the past few decades (Glover et al., 2010) and only at a limited scale.

TABLE 3.7 Published Estimates of Global and U.S. Soil Carbon Sequestration Potential on Managed Nonforested Lands

Study/Citation	Estimate	Scope
Global Estimates	**Gt/y CO_2e**	
Paustian et al., 1998	1.5-3.3	Improved cropland management, set-aside, restoration of degraded land
Lal and Bruce, 1999	1.7-2.2	Improved cropland management, restoration of degraded land[a]
IPCC, 2000	3	Improved cropland and grassland management, set-aside, agroforestry, restored peat soils
Lal, 2004	1.5-4.4	Improved cropland and grassland management, set-aside, agroforestry, restored degraded lands
Smith et al., 2008	5-5.4	Improved cropland and grassland management, set-aside, agroforestry, restored degraded lands, restored peat soils[b]
Sommer and Bossio, 2014	2.5-5.1	Improved cropland and grassland management, set-aside, agroforestry, restored degraded lands
Paustian et al., 2016b	2-5	Improved cropland and grassland management, set-aside, agroforestry, restored degraded lands, restored peat soils
Paustian et al., 2016b	4-8	Potential from the practices above, plus unconventional technologies including high root carbon input crop phenotypes and biochar amendments
Griscom et al., 2017	3-5	Conservation agriculture, agroforestry, improved grazing, avoided grassland conversion, biochar
Fuss et al., 2018	2.3-5.3	Improved cropland and grassland management, set-aside, agroforestry, restored degraded lands, restored peat soils
U.S. Estimates	**Mt/y CO_2e**	
Lal et al., 1998	275-639	Land conversion and set-asides, restoration of degraded land, improved management on cropland
Sperow et al., 2003	305	Improved cropland management, set-aside of marginal (highly erodible) cropland to grassland
Sperow, 2016	240	Improved cropland management, set-aside of marginal (highly erodible) cropland to grassland

continued

TABLE 3.7 Continued

Study/Citation	Estimate	Scope
U.S. Estimates	**Mt/y CO_2e**	
Chambers et al., 2016	250	Improved cropland and grassland management, set-aside of marginal (highly erodible) cropland to grassland[c]
Paustian et al., 2016a	500-800	Deployment of enhanced root phenotypes for major annual crops (assumes 2X root carbon input and downward shift in root distribution equivalent to native prairie grasses)[d]

[a] An additional 1-1.5 Gt CO_2e emission reduction was projected from biofuel CO_2 offsets.

[b] This study also included an estimate of "economic potential:" about 2.5 Gt/yCO_2e was achievable for < \$50 tCO_2.

[c] Based on estimate for widespread adoption of USDA National Resources Conservation Service's conservation practices on all private lands.

[d] Excluded nonirrigated semi-arid cropland with major water limitation on production.

NOTE: All values reflect technical or "biophysical" potential estimates that are not constrained by carbon price or policy design.

Approaches include creating perennial hybrids between related annual and perennial species (e.g., rice [Zhang et al., 2017a]; wheat [Hayes et al., 2012]; sorghum [Cox et al., 2018]) and domesticating naturally large-seeded wild perennials to further increase seed yield and quality (e.g., intermediate wheatgrass [Culman et al., 2013]; perennial sunflower [Vilela et al., 2018]). The major challenge is developing perennial grains with sufficiently high yields to be viable from an economic and food security perspective, with the most promising results to date shown for perennial rice (Zhang et al., 2017a). It has been argued that evolutionary tradeoffs between annual and perennial life histories (i.e., high allocation of resources to the seed in annuals vs to below-ground structures in perennials) inherently limit the potential for perennial crop replacement of annuals (Smaje, 2015). However, the extended vegetated duration of perennials (hence greater carbon assimilation) and positive feedbacks between greater root development and nutrient acquisition in some soils do not preclude the potential for high-yielding grain production from perennial crops (Crews and Dehaan, 2015; Jansson et al., 2010).

IMPACT POTENTIAL

Carbon Dioxide Removal Capacity

For all managed terrestrial carbon sinks, potential carbon removal rates are conditioned on the biological/ecological capacity of the technologies employed as well as economic and social acceptance factors. The majority of published estimates of carbon sequestration rates can be considered *technical potentials* in which achievable rates per unit area are multiplied by estimates of the maximum feasible land areas for implementation. Such rates and capacities represent an upper limit that does not fully reflect economic constraints, including land availability for competing uses, or other social or policy constraints. A lower *economic potential* for carbon sequestration reflects the fact that adopting more carbon-friendly land-use practices likely requires an economic incentive (although some amount of carbon stock gains may be achievable at negative costs). Combined ecological and economic analyses have been used to estimate marginal supply curves for carbon storage (e.g., McCarl and Schneider, 2001; Murray et al., 2005; Smith et al., 2008), where each additional increment of storage comes at a higher cost per unit carbon stored. However, relatively few formal analyses have considered the economic potentials, given the complexity and high degree of uncertainty in future market conditions. Finally, the *actual potential* storage achievable would factor in additional constraints related to social acceptance and policy implementation. Estimates for the major land uses in the United States and globally are presented below.

Conventional Forest Practices

Afforestation/Reforestation

For the United States, comprehensive analyses have shown that the potential carbon removal from afforestation/reforestation ranges from 0.0 to 0.45 Gt CO_2 annually, over a period of approximately 50 to 100 years (Table 3.8). The soil component of this increase in carbon removal may be significant according to a recent study that estimated a range of 0.05 to 0.08 Gt/y CO_2 (Nave et al. 2018).

At the global scale, the range of published estimates for afforestation/reforestation is large, from 2.7 to 17.9 Gt CO_2 annually based on global analyses using top-down approaches for the high end of the range, and bottom-up approaches for the low end (Table 3.8). The wide range reported in studies represents different assumptions and modeling approaches, and variable prices or incentives for implementing activities.

TABLE 3.8 Total Global and U.S. Estimates of Carbon Removal Potential for Forestry Activities

Study/Citation	Estimate Gt/y CO_2e	Scope
	Global Estimates	
Nabuurs et al., 2007	4.0	Afforestation/Reforestation
Griscom et al., 2017	2.7-17.9	Afforestation/Reforestation
Smith et al., 2016	4.0-12.1	Afforestation/Reforestation
Nabuurs et al., 2007	5.8	Improved forest management
Griscom et al., 2017	1.1-9.2	Improved forest management
	U.S. Estimates	
Nabuurs et al., 2007	0.445	Afforestation/Reforestation
McKinley et al., 2011	0.001-0.225	Afforestation/Reforestation
Jackson and Baker, 2010	0.15-0.4	Afforestation/Reforestation
Nabuurs et al., 2007	1.6	Improved forest management
McKinley et al., 2011	0.029-0.105	Improved forest management

At the low end of the range, the assumed price of carbon is low and secondary impacts are few—for example, sufficient marginal agricultural land is available and landowners are willing to participate in mitigation. At the high end, the price of carbon would be as high as \$100 tCO_2, and tens of millions of hectares would be incentivized to convert from crop or grass production to forest. Food production would be significantly impacted, so that the total land area that could be reforested or afforested is constrained by the higher value of alternative land uses (i.e., food price impacts from cropland conversion). The net CO_2 reduction may be reduced over time by leakage (i.e., timber harvest elsewhere to meet continued economic demand for forest products), and concerns about permanence (subsequent clearing or natural disturbances).

Improved Forest Management

The potential of improved forest management ranges from 0.03 to 1.6 Gt/y CO_2 for the United States and from 1.1 to 9.2 Gt/y CO_2 for the world based on published studies (Table 3.8). Improving forest management on existing forestland faces limited to no competition with other land uses compared with reforestation/afforestation, because this activity involves no change in land use. However, the cost may be higher because of the large area that must be treated to achieve similar results, and forest management would need to involve a much larger percentage of forest landowners than has ever participated in any incentive program. As with afforestation/reforestation, both leakage and risk of reversal from disturbances could reduce potential carbon removal gains over time.

Near-term forest carbon removal potentials

For a recent and practical reference point, summing the forestry activities proposed by countries in their intended nationally determined contributions (INDCs) to the Paris agreement yields a total expected global carbon removal benefit from afforestation/reforestation and improved forest management (excluding avoided deforestation) of approximately 1.0 Gt CO_2. This is comparable to the low end of the estimates reported above, because the INDCs were purposely modest, representing what different governments considered achievable toward a target of limiting climate change to 2°C.

A modest program of afforestation/reforestation near the lower end of published ranges could be 0.15 Gt/y CO_2 for the United States and 1.0 Gt/y CO_2 for the world, taking into consideration availability of land and secondary impacts (described later in this chapter). Considering land constraints, a practical upper limit for carbon removal from afforestation/reforestation would be about 0.4 Gt/y CO_2 for the United States and likely no more than 6.0 Gt/y CO_2 for the world (Box 3.1). Similarly, the near-term carbon removal from improved forest management is likely to be near the lower end of these ranges, about 0.1 Gt/y CO_2 for the United States and 1.5 Gt/y CO_2 for the world. The upper limit of a more aggressive program to improve forest management could achieve a rate of carbon removal of 0.2 Gt/y CO_2 for the United States and 3.0 Gt/y CO_2 for the world.

Frontier Forestry Practices

Increased Use and Preservation of Harvested Wood Products

If most (up to 80 percent) of discarded wood products and associated wood wastes from current harvest and manufacturing were placed in a landfill designed for slow decomposition, then this would create an additional sink of 0.1 to 0.3 Gt/y CO_2 in the United States and 0.2 to 0.8 Gt/y CO_2 globally, which could be extended indefinitely as long as construction of such landfills continued. Preservation of currently harvested

BOX 3.1
SUMMARY OF TERRESTRIAL CARBON REMOVAL ESTIMATES

Land availability and the degree of adoption of carbon removal practices are major constraints on land-based NETs. Achieving the uppermost estimates for conventional practices (afforestation/reforestation, improved forest management, improved cropland and grassland management) shown in Tables 3.7 and 3.8 is highly unlikely because of the following constraints: the availability of land for conversion from current uses, leakage and risk of reversal from disturbances, and economic and behavioral barriers to full adoption on all available land.

Weighing these constraints, the committee provides estimates for "practically achievable" CO_2 removal rates that are feasible, with current technologies and do not involve using protected forest areas or compromising food supply or biodiversity. The estimates include additional carbon removal capacity from frontier technologies that are not constrained by land availability (e.g., carbon burial approaches, substitution of high carbon input phenotypes within current land-use area distributions).

Implementation	**Forest**	**Agriculture**	**Total**
United States	-------------- Gt/y CO_2 --------------		
Practically achievable	0.25	0.25	**0.5**
Practically achievable + frontier technology	0.35	0.8	**1.15**
Global			
Practically achievable	2.5	3	**5.5**
Practically achievable + frontier technology	3.3	8	**11.3**

wood plus increased harvesting of secondary forests to use all available growth (sustainable harvest) has the capacity to remove 0.1 to 0.7 Gt/y CO_2 in the United States and 0.8 to 9.3 Gt/y CO_2 globally. This could be accomplished without involving protected or intact forests, or affecting food supply or biological diversity.

Zeng et al. (2013) estimated that the global potential of green-tree burial was between 1.0 and 3.0 Gt/y CO_2, with the lower end of this range roughly doubling the current global harvest and affecting about 800,000 ha of forestland. They excluded agricultural land, protected areas, inaccessible forests, and wood used for other purposes such as timber and paper. To date, this proposed approach has not been tested, although the technology is simple and easily applied.

Conventional Cropland and Grassland Practices

During the past 20 years, several estimates of the soil carbon sequestration potential for the United States and the world have been released (Table 3.7). Nearly all represent a technical or "biophysical potential" assuming nearly complete practice adoption. As such, they represent upper-bound estimates of the carbon sequestration potential for the practices considered. However, the estimates do account for limitations relating to land availability, such as the limited land-use conversions to high carbon storage practices (e.g., permanent grassland set-aside that could occur without compromising food and fiber production). Most published estimates use aggregate data stratified by broadly defined land-use and climate categories (in some cases soil type), together with representative per hectare rates for different land-use/management practices determined from long-term field experiments or other measurements (e.g. chronosequence).

Frontier Cropland and Grassland Practices

Detailed analyses of the global sink potential of the frontier practices described earlier (i.e., high carbon input phenotypes, deep soil inversion) have not been published, with the exception of biochar amendment. Recent estimates of the global carbon sink capacity of large-scale deployment of biochar application to soil suggest gigaton per year potential (e.g., 6.6 Gt/y CO_2e by Woolf et al. [2010], 2.6 Gt/y CO_2e from Smith [2016], and 0.5-2.6 Gt/y CO_2e by Fuss et al. [2018]). Because biochar applications mainly target existing current cropland where large addition rates (up to 50 tC/ha; Smith, 2016) are agronomically feasible, there is no land constraint for application, although there is for biomass feedstock sourcing (see Land Requirements section below). Key uncertainties remain, including net life cycle GHG impacts, long-term impacts on crop productivity and economic feasibility of large-scale biochar deployment.

Other Radiative Impacts

Forest

The impact on climate from reducing CO_2 by afforestation/reforestation may be partially offset by albedo changes (the proportion of radiation reflected by the land surface). Generally, an increase in forest cover reduces surface reflectivity causing more surface warming, whereas a harvest increases surface reflectivity causing a cooling effect, implying that the effect of increasing harvest or forestland clearing would have a less negative impact on climate than indicated by only accounting for GHG changes. Albedo effects are typically larger in the years immediately following harvest, last longer for land use changes, and are most significant in response to changes in conifer coverage above the snow line (Cherubini et al., 2012; Holtsmark, 2015). These effects on climate forcing are usually less influential than the effects of changes in GHGs but may be highly variable (Anderson-Teixeira et al., 2012). In general, afforestation/reforestation in boreal zones will have a warming effect that exceeds the cooling effect of reducing GHGs, and the opposite effects in the tropics. In temperate zones, the effects are highly variable in space, depending on vegetation type, timing of snow cover slope, aspect, and other factors. Recent work has extended the analysis of radiative effects to include nonradiative processes such as air turbulence, which may have larger and locally more variable effects than albedo changes (Bright et al., 2017).

Cropland/Grassland

In designing and implementing CO_2 removal strategies involving agricultural land management, impacts on other GHGs, particularly N_2O and CH_4, are of paramount importance. Agricultural soils are the single largest source of N_2O, driven by the large additions of nitrogen to promote plant growth. Flooded cropland soils (rice) are a major CH_4 source. Soil-based CO_2 removal strategies should avoid requiring additional nitrogen fertilizer, which has large embodied fossil carbon emissions for its manufacture, in addition to impacts on N_2O emissions (van Groenigen et al., 2017). Thus, any additional nitrogen requirements to support increased plant production and carbon inputs should be sourced from more efficient use of nitrogen already applied to agricultural soils as well as from biological nitrogen fixation. Management options that offer synergisms with both increased soil carbon stocks and reduced N_2O (and CH_4) emissions should be prioritized.

Agricultural practices to increase CO_2 removal likely have minimal impact on other (e.g., aerosols, albedo) radiative forcing factors. For example, conversion of winter-fallow bare soils to lighter surface of senescent winter vegetated cover, as well as reduced tillage systems that retain surface residues, increases albedo in most cases, providing a small cooling effect (Davin et al., 2014). Most other agricultural carbon removal practices will have negligible impacts on albedo.

Current Commercial Status

The current commercial status of carbon removal via terrestrial land-use options remains limited but is growing. Only a few compliance cap-and-trade markets for GHG reductions are in operation (e.g., European Union, California), and for most of those, land use–based offsets (i.e., allowable emission reduction from noncapped entities) play a minor role, if included at all. Hence, the demand for, and thus the monetary value of, terrestrial carbon storage remains still low. More direct financing of carbon sequestration projects involving agriculture and/or forestry exists in the voluntary carbon/emission reduction markets. In 2016 the total volume of forestry and land use project carbon reductions was 13.1 Mt CO_2e, at an average price of \$5.10 t/CO_2, for an aggregate value of \$67 million. Greater than 95 percent of the CO_2 reduction activities focused on forest biomass carbon, of which REDD+ (Reduced Deforestation and Forest Degradation Plus) projects dominated with 75 percent of total CO_2 reductions (Hamrick and Gallant, 2017). In the United States, an indirect measure of the commercial value, to the landowner, are the subsidies paid by government for implementation of conservation practices that also promote carbon sequestration. In many cases, these payments address multiple environmental outcomes and often take the form of cost shares or loans, as opposed to direct payments for tonnes of carbon sequestered as in voluntary or cap-and-trade markets. Chambers et al. (2016) estimated that conservation payments that promoted soil carbon storage averaged around \$60M/y from 2005 to 2014, with an estimate carbon storage increase of 13 to 43 Mt C on U.S. cropland, which equates to a carbon price of \$5-17/t CO_2e.

Land Requirements and Competition for Land among Alternative NETs

Although scientific uncertainty about the amount of carbon sequestered locally from improved land management practices is low, uncertainty about far-field impacts caused by the long-term effects of climate change and the economic feedback is high. An important consideration is that land requirements and competition for land cuts across several of the NETs in this report—particularly, afforestation/reforestation and BECCS. Soil carbon sequestration and biochar use land, but do not compete for land, which can still be used for the same purpose. Each of these technologies were evaluated separately, but their maximum potential cannot be realized simultaneously. Here we examine the land requirements for these different activities and compare them with current land uses and potentially available land for additional carbon removal. Table 3.9 summarizes the practically achievable ranges of carbon removal from forestry and BECCS, including an estimate of the land area required for each.

Forestry

Even relatively low amounts of carbon removal and carbon sequestration from afforestation/reforestation (0.15 Gt/y CO_2) in the United States would require converting 3-4 Mha of nonforested land to never-harvested forest. Improved forest management would require changes on 11-19 Mha of existing forest for a modest increase in carbon removal of 0.1 Gt/y CO_2. Global land requirements for afforestation/reforestation to achieve 1.0 Gt/y CO_2, and improved forest management to achieve 1.5 Gt/y CO_2, are 70-90 Mha and more than 1,000 Mha of existing forestland, respectively. These levels of activity should be achievable at low carbon prices (i.e. \$10-50/Mg CO_2), but safeguards would be necessary to reduce negative impacts and ensure permanence. In addition, implementation would require a very high participation rate by landowners.

TABLE 3.9 Range of Practical Annual CO_2 Removal Fluxes and Associated Land Requirements for Estimates Presented in This Report

Activity category	**Carbon removal-low (Gt/y CO_2)**	**Carbon removal-high (Gt/y CO_2)**	**Area-low (Mha)**	**Area-high (Mha)**
U.S. afforestation/reforestation[a]	0.15	0.4	3-4	16-20
Global afforestation/reforestation[b]	1.0	6.0	70-90	350-500
U.S. BECCS[c]	0.52	1.5	0	78
Global BECCS[c]	3.5-5.2	10.0-15.0	0	380-700

[a] Based on Jackson and Baker, 2010. Would require a CO_2 price of \$15/t for carbon removal-low and \$50/t for carbon removal-high.

[b] Based on Griscom et al., 2017 and Smith et al., 2016.

[c] Refer to Chapter 4 for sources of estimates. At the low end, biomass is sourced from existing land uses so no new land dedicated to BECCS is required.

NOTES: See Chapter 4 for the source of estimates for BECCS. Activity categories that do not require land-use shifts (e.g., agriculture, improved forest management) are not included in the table.

Although higher levels of carbon removal are technically achievable from afforestation/reforestation, attaining 0.4 Gt/y CO_2 in the United States would require much larger areas of land (up to 20 Mha) and a high carbon price (i.e., >$50/Mg CO_2). Globally, the area of land needed to support a 6 Gt/y CO_2 carbon removal from afforestation/reforestation would require up to 500 Mha of land. These higher levels of afforestation/reforestation would have significant negative impacts, including reduced food production and increased food prices.

Higher levels of improved forest management in the United States to achieve 0.2 Gt/y CO_2 would require 22-38 Mha of existing forestland. Worldwide, the levels to achieve 3.0 Gt/y CO_2 would require more than 2,500 Mha of existing forestland. These management changes could result in leakage by shifting some harvesting elsewhere and would require participation by most private landowners, which would be difficult to achieve.

Agriculture

The majority of management practices considered for carbon removal in agricultural soils do not involve changes in land use and hence would largely be operative on the existing land base devoted to agricultural production. To the extent that many practices improve soil health and productivity, carbon removal activities could contribute toward meeting increased food and fiber demands without increasing the area of land under agriculture. The main activity that could contribute to displaced agricultural production and potential land-use conversions elsewhere would be setting aside cropland into perennial grassland (or forest, see above), for conservation purposes. To the extent that degraded or otherwise marginal agricultural lands are targeted for set-asides, leakage effects (i.e., displacement of agricultural production resulting in land-use conversion and soil carbon losses elsewhere) would be minimal. Currently, roughly 9.8 Mha of cropland is in set-asides under the U.S. Conservation Reserve Program (CRP). At its height during the late 1990s, the CRP area exceeded 13 Mha (Mercier, 2011), which resulted in estimated leakage of around 20 percent of the sequestered carbon (Wu, 2000), although potentially larger leakage has been suggested (Murray et al., 2007).

BECCS

As discussed in Chapter, 4 the committee calculated the low-end estimate for this approach assuming that sources of biomass from existing land uses (e.g., wood and other unutilized organic waste) are sufficient and no land-use changes are necessary.

Dedicated land requirements for the high-end estimate for the United States are based on reported economically feasible energy crops that could produce up to 0.65 Gt CO_2e annually (U.S. DOE, 2016), Assuming an average productivity of 18 t CO_2e per ha, this level of production would require 36 Mha of land. Scaling this estimate up to our high end of 1.4 Gt CO_2e indicates a requirement of 78 Mha, equivalent to almost 20 percent of the current agricultural land base (Table 3.9). Smith et al., 2016 estimate the global land area required to deliver 12 Gt/y CO_2e at approximately 380-700 Mha in 2100 for high productivity energy crops, such as willow, poplar short-rotation coppice, and miscanthus. Therefore, the large-scale implementation of BECCS is expected to compete with terrestrial carbon capture and storage initiatives, as well as with food production (e.g., Smith et al., 2010) or the delivery of other ecosystem services (e.g., Bustamante et al., 2014).

Aggregated Carbon Removal Land Requirements and Availability Of "Marginal Land"

The total area of land managed for agriculture and forestry is 791 Mha in the United States and 7,130 Mha globally (Table 3.10). Some of this land may be considered marginal by landowners, which could serve as an indicator of the amount of land that could be shifted to another use without significant effects on production of necessary services, particularly food. There is no generally accepted definition of marginal land (it is an economic decision that varies over time or is based on subsistence needs), but an indicator in the United States is the ca. 10 Mha of farmland currently enrolled in the CRP. A similar global estimate is more difficult to determine, but one recent study estimated that the global pool of marginal land is about 1,300 Mha. This land supports about one-third of the world's population and therefore only a fraction would be available for afforestation/reforestation and BECCS. Another global analysis estimated

TABLE 3.10 Managed Land Area by Selected Land-Use Categories in 2015 (Mha)[a]

Category	Forest	Cropland	Grassland	Total
U.S.[b]	293	163	325	781
World[c]	2,429	1,426	3,275	7,130

[a] U.S. definitions according to EPA, 2017. World definitions according to FAOSTAT database.

[b] Data from EPA, 2017.

[c] Data from FAOSTAT database, accessed March 11, 2018.

that 760 Mha of land are available and suitable for afforestation in IPCC non-Annex 1 countries, which are mostly in tropical and subtropical biomes (Zorner et al., 2008).

Because new land dedicated to BECCS would likely be planted with fast-growing species such as miscanthus (on more productive sites), the area required per unit of carbon removal would be much less than that required for afforestation/reforestation. Humpenöder et al. (2014) highlighted the trajectories and relative land requirements for afforestation and BECCS (Figure 3.3) using a land-based modeling approach that simulated a similar level of carbon removal as the high-end calculation in this report. They suggest that the area required for BECCS is much lower than that required for afforestation (Table 3.9) based on strongly increasing yields per hectare for herbaceous biofuel, up to 25-30 t/(ha y) C, compared with afforestation yields that are estimated at a much lower rate for natural regeneration of forests, about 2-6 t/(ha y) C (Table 3.1). However, as noted in the BECCS chapter, the temporal nature of bioenergy production should also be considered.

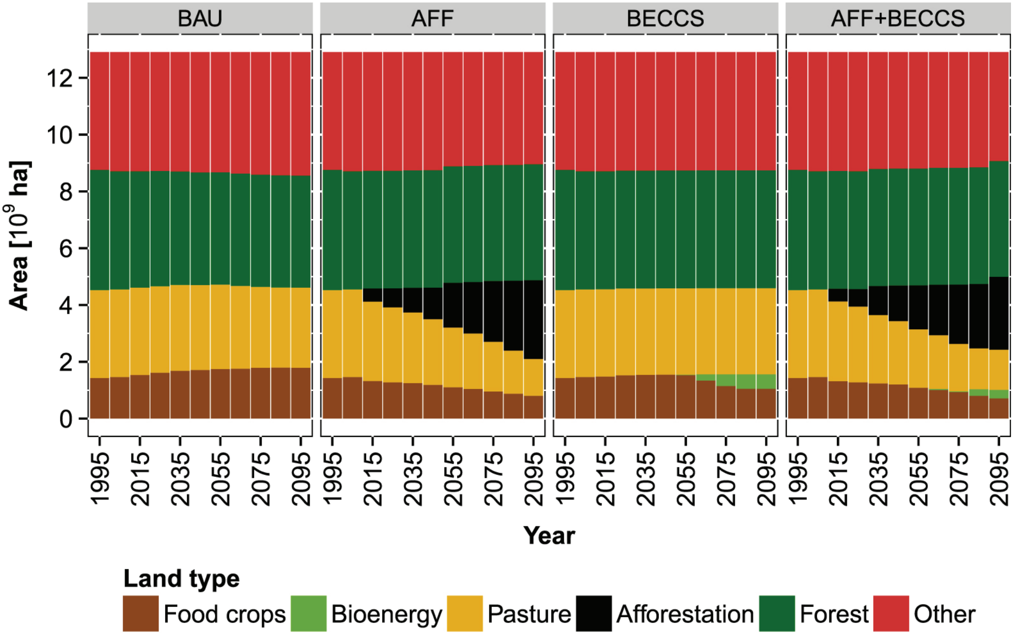

FIGURE 3.3 Simulated time series of global land use for business as usual (BAU), afforestation (AFF), BECCS, and AFF + BECCS.
NOTES: Both increased afforestation and BECCS require additional land that significantly impacts land used for food and pasture. By the end of the century, global area required for these activities is more than five times larger in case of afforestation (~2800 Mha) compared to BECCS (~500 Mha). SOURCE: Adapted from Humpenöder et al., 2014.

In summary, at the low end of the committee's estimates for carbon flux and capacity for afforestation/reforestation and BECCS, any competition for land between these two NETs would not be significant (because BECCS biomass could be sourced entirely from existing land uses), nor would there be competition for land currently required for food production. Land requirements for afforestation/reforestation both in the United States and globally could be met by tapping into land considered "marginal" for food production, although globally, some of the required marginal land is used to support population needs for food and fiber. At the high end shown in Table 3.9, the total area required for afforestation/reforestation and BECCS combined would likely exceed the availability of marginal land. Considering the additional impact on land required for food production, this level of carbon removal is not likely to be realized.

ESTIMATED COSTS OF IMPLEMENTING TERRESTRIAL CARBON SEQUESTRATION AT SCALE

The direct costs of establishing new forests and performing management activities in different regions are well known based on experience, and several studies have revealed how landowners would respond to various carbon price levels. However, scaling direct costs to high levels of activity is a challenge. Estimates of indirect costs and impacts on carbon associated with collateral effects such as offsetting land-use change and commodity production are available, but knowledge of these effects is limited by the ability of macro-economic models to simulate complex responses.

The costs of different forestry practices are highly variable by practice and region, and their estimates when scaling to a high level of carbon removal differ wildly depending on the method used to estimate feasibility (Alig, 2010; Figure 3.4). Engineering methods to estimate costs result in higher costs at the low end of total tons sequestered, and lower costs at higher levels of carbon removal, compared with econometric or optimization approaches that account for market adjustments.

Cost estimates for implementing conventional soil carbon sequestering practices (e.g., planting cover crops, changing tillage practices and crop rotations) are readily available as state- and regionally-specific farm budgets.[1] However, more general information on future costs and projected willingness to adopt carbon sequestering practices as a function of carbon prices are mainly available from academic studies. While varying for different geographic areas and farming systems and practices (Alexander et al., 2015), many estimates suggest significant adoption rates of improved cropping

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[1] e.g., https://www.ers.usda.gov/data-products/commodity-costs-and-returns.

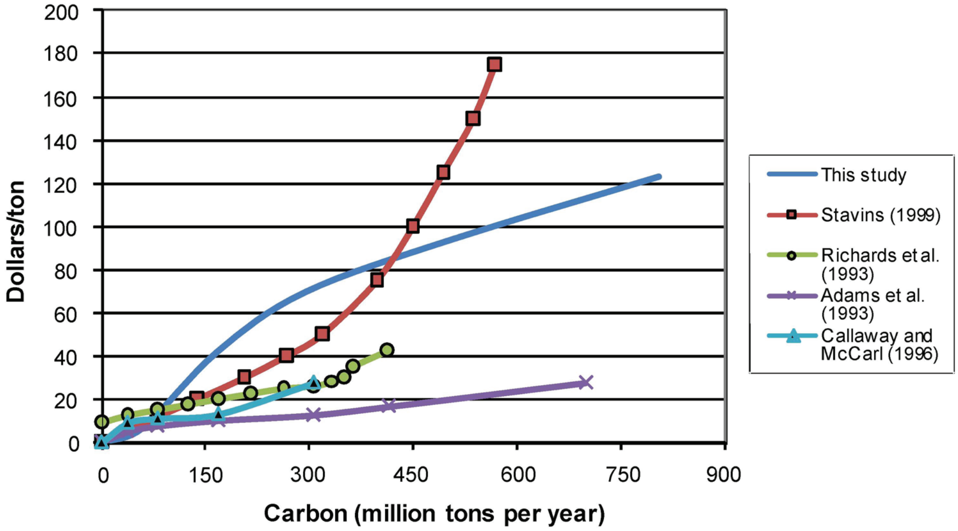

FIGURE 3.4 Comparison of marginal cost curves for forest carbon sequestration in the United States by Lubowski et al., 2006 with optimization models (Adams et al., 1993; Callaway and McCarl, 1996) and bottom-up engineering cost methods (Richards et al., 1993).
NOTE: "This study" in the graphic refers to Lubowski et al., 2006. SOURCE: Adapted from Alig, 2010.

practices could occur at values <\$50 tCO_2e (Tang et al., 2016). In a global analysis, Smith et al. (2008) estimated economically-achievable GHG reductions (>90 percent of which were from soil carbon sequestration) of 1.5, 2.2, and 2.6 Gt/y CO_2e at carbon prices of 0-20, 0-50, and 0-100 USD/tCO_2e, respectively. Economic feasibility and marginal cost curves for nonconventional (frontier) carbon sequestering technologies described earlier are not known.

An economic optimization model used to estimate forestry, agriculture, and bioenergy supply functions for emissions reductions in the United States (Figure 3.5) indicated that at low carbon prices, forestry and agriculture opportunities were about equal in terms of economic potential carbon removal and higher than bioenergy. At higher prices, agriculture had the largest impact on carbon removal followed by afforestation and forest management.

SECONDARY IMPACTS

The impacts of changes in land management on biodiversity, water, and other land attributes may be positive or negative depending on types of changes in land cover and site-specific land characteristics. For example, timber harvesting changes forest

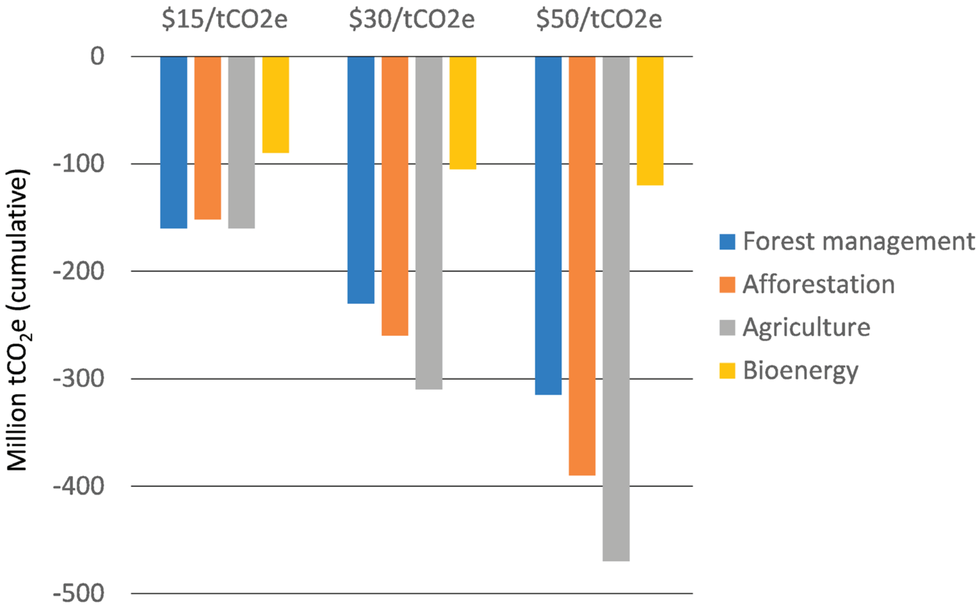

FIGURE 3.5 Mitigation potential of land-based NETs in the United States for three carbon price scenarios ($15, $30, and $50 per ton CO_2e). Negative number indicates removal of CO_2 from the atmosphere. Estimates from the FASOM model reported by Baker et al., 2010 and Jackson and Baker, 2010.

structure, composition, and productivity, which in turn affects many other properties and services of forests such as wildlife habitat, biodiversity, and runoff (Venier et al., 2014). These impacts may be profound and long-lasting by establishing spatial patterns that broadly affect forest and landscape ecology, similar to the effects of many natural disturbances. Some studies show that managing for carbon in particular forests can decrease biodiversity, because habitat is reduced for species that depend on disturbance to create habitat (Lawler et al., 2014; Martin et al., 2015). Impacts of harvesting roundwood on forest ecology are significant and should be considered in formulating policies as well as assessed through observations, although additional studies are needed to determine how to assess such impacts at different scales. Turner (2010) highlighted key concepts of how disturbances and recovery have profound and long-lasting impacts at stand and landscape scale as forests recover. Fundamental ecosystem processes and functions are affected. For example, productivity and mortality are strongly related to time since disturbance, and disturbances create spatial heterogeneity that can be essential for some wildlife species.

Co-Benefits of Soil Carbon Sequestration (SCS) Practices

In addition to CO_2 removal, increasing soil carbon contents provides benefits for soil health and other ecosystem services, including enhanced carbon and nutrient pools, water storage, improved soil structure, aggregation, and water and air infiltration, as well as reduced soil erosion and enhanced soil biodiversity (Al-Kaisi et al., 2014; Lefèvre et al., 2017). A study of ecosystem services in conservation planning for targeted benefits vs co-benefits found that inclusion of ecosystem services within a conservation plan may be most cost-effective when they are represented as substitutable co-benefits/costs, rather than as targeted benefits (Chan et al., 2011). Well-managed soils that enhance soil carbon also promote soil biodiversity, which in turn enhances the function and metabolic capacity of soils and plays a crucial role in increasing food production and soil resilience to climate change. Increasing soil organic matter contents will facilitate (1) nutrient storage in SOM; (2) nutrient recycling from organic to plant-available mineral forms; and (3) physical and chemical processes that control nutrient sorption and availability. The dynamic nature of managed soils is what makes soils function and supply ecosystem services (Lefèvre et al., 2017).

RESEARCH AGENDA

Basis for Research Budget Estimates

The proposed budget for terrestrial basic and applied research components for a national research agenda aligns with the current budget for various soil and plant research established by the National Institute of Food Agriculture (NIFA) and the USDA Agriculture and Food Research Initiative (AFRI). The AFRI research program for various components allocates $500K to $750K/y per research project for a period of 3 to 5 years for research programs such as Plant Health and Production, Bioenergy, and Animal Health. Generally, in the estimates quoted for different research activities, the committee allocated $300K per scientist year for postdoctoral-level research, plus funds for administrative and technician support, equipment, travel, publications costs, and other expenses specific to the research described. The cost of each component of the research agenda is summarized in Table 3.11.

TABLE 3.11 Costs and Components of a Terrestrial NET Research Agenda

	Recommended Research	Estimated Research Budget ($M/y)	Timeframe (y)	Justification
Basic Research	High carbon input crop phenotypes	40-50	20	The DOE/ARPA-E ROOTS program is currently funded for $35M total, allocated to 10 multiyear projects. Thus proposed funding is a 4-5X increase over this level
	Soil dynamics at depth	3-4	5	Funding to initiate 4-6 projects per year
	Harvested wood preservation	2.4	3	Funding to initiate 3 multiyear projects at $800K each, involving representative locations
	Biochar studies	3	5-10	Funding for 3-5 projects per year to assess biochar amendment impacts for different management systems and soil types
Development and Measurement/Monitoring	Monitoring of forest stock enhancement projects	>5	≥3	System development of $1M/y for 3 years Continuous operation -$4M/y to staff a small office to analyze data, coordinate field checks, develop reports Improving international forest monitoring and reporting—10 to 20 times the amount needed in the United States
	National on-farm monitoring system	5	Ongoing	Augmentation of USDA's existing NRI system
	Data-model platform for predicting and quantifying agricultural soil carbon removal and storage	5	5	Initial development focuses on systems integration, including of existing data sources and models

TABLE 3.11 Continued

	Recommended Research	Estimated Research Budget ($M/y)	Timeframe (y)	Justification
Demonstration	Forest demonstration projects: increasing collection, disposal, and preservation of harvested wood; and forest restoration	4.5	3	Demonstration projects to improve disposal and collection of wood products after use (three 3-year projects at $500K/y each); 3 multiyear projects for preserving harvested wood in different environments (500K/y each); and 3 multiyear projects to demonstrate carbon benefits of forest restoration in different geographic regions ($500K/y each)
	Experimental network improving agricultural soil carbon processes	6-9	≥12	10-15 sites at a cost of $600K/y per site
Deployment	Social sciences research on improving landowner responses to incentives and equity among landowner classes	1	3	Extension and outreach educational programs for transferring research findings and technologies to farmers and practitioners. Funding for initiation of 3 multiyear projects
	Research on GHG and social impacts of reducing traditional uses of biomass for fuel	1	3	Funding for initiation of 1 multi-year project
	Scaling up agriculture sequestering activities	2	3	Support for initiation of 4-5 regional projects per year to identify solutions to overcome barriers to adoption

Basic Research

High Carbon Input Crop Phenotypes

Research is needed to develop crop varieties with altered root morphology and biomass (e.g., more roots, deeper root distributions, more recalcitrant to decomposition) to add and maintain high root carbon inputs to soil, while maintaining high aboveground yields. Specific research areas include crop breeding and selection for annual crops with larger and deeper roots, perennialization of major grain and oilseed crops, advanced root phenotyping technologies, new crop performance trials, and soil and ecosystem responses to new crop varieties. Such a research program can build on the recently initiated ROOTS (Rhizosphere Observations Optimizing Terrestrial Sequestration) program established by ARPA-E.[2] The cost for this research is approximately $40-50M/y for an initial 20-year period and could be conducted through USDA, the National Science Foundation (NSF), and/or the Department of Energy (DOE). For comparison, current annual research and development (R&D) funding for conventional crops improvement and genetics in the United States is approximately $1.5 billion from the public sector and $1.8 billion from the private sector (Fuglie and Toole, 2014).

Soil Carbon Dynamics at Depth

Research is still limited on the controls on decomposition and stabilization of SOM in subsoil, that is, below 30 cm. Several promising technologies to increase soil carbon stocks (e.g., prairie restoration, deep soil inversion and carbon burial, enhanced root phenotypes) are based on increasing carbon additions to subsoil layers. Studies are needed to determine how stabilization and residence times of organic residues vary as a function of depth gradients in aeration, microbial community composition, soil physiochemical properties (e.g., soil texture, soil mineralogy), and plant (root) residue composition. The cost for this research is approximately $3-4M/y for 5 years and could be conducted by USDA and NSF.

Harvested Wood Preservation

Research is needed in two areas: The first area is landfill designs for achieving the lowest possible rate of wood decomposition. Reducing wood decomposition has

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[2] Projects in the ARPA-E ROOTS program seek to develop advanced technologies and crop cultivars that enable a 50 percent increase in soil carbon accumulation while reducing N_2O emissions by 50 percent and increasing water productivity by 25 percent. For more information see: https://arpa-e.energy.gov/?q=arpa-e-programs/roots.

not been a stated goal of landfill designs; rather, they have been designed to contain buried waste, collect contaminated precipitation that percolates through the waste (leachate), and collect and control gas emissions. A large body of landfill design research at several representative sites forms a foundation for focused attention on minimizing wood decomposition (U.S. Forest Service [USFS], U.S. Environmental Protection Agency [EPA], and NSF; Cost: $2.4M/y for 3 projects lasting 3 years). The second area is integrated assessment of net greenhouse balance, costs, and required land, including the implications for worldwide consumption of wood products and their life cycle emissions. Any change in consumption of wood products will have widespread effects on emissions related to other sectors of the economy, for example, construction or material transportation. (For the existing research capacity and cost, see the integrated assessment section in the BECCS chapter.)

Biochar Amendment Studies

Although much is already known about residence time in soil for different types of biochar and how biochar characteristics vary as a function of the feedstock and the pyrolysis process used, additional research is needed to assess secondary impacts of different biochars on crop performance, nutrient cycling and retention, and N_2O and CH_4 emissions from soils, all of which affect the net GHG consequences of biochar amendments. In addition, research to produce full life cycle analyses that consider the alternative fates/uses of feedstocks from which the biochar is produced (Paustian et al., 2016a) are needed for a comprehensive assessment of net carbon removal potentials from biochar amendments.

Development and Measurement and Monitoring

Monitoring of Forest Carbon Stock Enhancement Projects

For private and public forestlands, USFS should develop a plan to monitor recommended carbon stock–enhancing activities, conduct statistical sampling of total ecosystem carbon stored in a subset of projects, and develop local “climate impact factors” that also account for biophysical effects. It is time consuming and expensive to directly measure the effects of many small projects on net GHG emissions; therefore, approaches that could achieve accurate average estimates for aggregates of projects (based on remote sensing and validated expansion factors) are needed to reduce transaction costs. Additional needs are to monitor leakage (which is a global phenomenon) and to use the monitoring system to attribute observed changes in carbon removal to management activities vs increasing CO_2 or climate change. Monitoring leakage could require a new LiDAR satellite dedicated to mapping global forestry activities. Knowledge and monitoring of lateral transfers of carbon from land to inland waters are lacking, and these transfers are not currently detected by remote sensing or operational field inventories. The substantial capacity of current remote sensing and field monitoring could be built on to address the additional needs described here. For example, the USFS Forest Inventory and Analysis (FIA) program is funded at approximately $70M/y, collects continuous field data on status and trends of U.S. forests, and collaborates with NASA to develop methods to integrate remote sensing data with field data. Internationally, the status of monitoring is highly variable, with many countries lacking field measurements and capacity to implement monitoring programs. However, there is a significant international aid effort to improve capacity in forest monitoring at the country scale, as well as to advance research on global monitoring capability using satellites. The research cost for the United States only is approximately $1.0M/y for 3 years for system development, and continuous operation would cost approximately $4.0M/y to staff a small office to analyze data, coordinate field checks, and develop reports. A significant contribution to improving international forest monitoring and reporting, including detection of leakage worldwide, would require about 10 to 20 times the amount needed in the United States.

A National On-Farm Soil Monitoring System

USDA should fully implement a national on-farm soil monitoring system on existing National Resource Inventory (NRI) points on cropland and grassland. Full buildout to approximately 5,000-7,000 NRI locations with soil sampling and analysis carried out at intervals of 5-7 year (on an annual rotating basis similar to the FIA system) is recommended. Similar systems already exist in many countries, including in the European Union, Australia, New Zealand, and China (van Wesemael et al., 2011). This system would provide an ongoing data stream to improve national-scale soil carbon inventory systems and reduce uncertainties. Such a monitoring system has the potential for broader utility for tracking and assessment of soil health and to support long-term sustainability of soils for the U.S. agricultural economy, which has a gross domestic product of more than $135 billion from farm output alone. The cost for this system is $5M/y as an augmentation of USDA's existing NRI system.

Model-Data Platform for Quantifying and Forecasting Carbon Removals by Soils

For implementation of soil carbon sequestering practices at Gt/y scales, improved platforms for quantifying soil carbon storage accurately and cost effectively are needed (Figure 3.6). Such systems should integrate data from a repository of existing and new experimental field sites to inform process-based land use/ecosystem models that can be independently validated using on-farm soil monitoring networks. Spatial data layers of model drivers (e.g., weather, soil maps, topography), together with comprehensive remotely sensed activity data on management practices (e.g., crop species, presence/absence of cover crops, tillage system, irrigation, vegetation productivity) provide the main data inputs to the model. Potential crowd-sourcing of farm management information (e.g., nutrient management) from the land users themselves can provide data that cannot be readily obtained from remote sensing. Such a system is scalable to estimate national-scale outcomes of CO_2 removals over time as a function of land use policies (e.g. for national GHG inventory reporting) as well as to provide information on field- and local-scale dynamics that can inform policies based on carbon markets and/or sustainable product supply chains supported by agricultural industries. Many component parts of such a system (e.g. field experiment networks, remote sensing data) already exist and could be leveraged. Funding of $5M/y for a 3-year development period followed by annual operating costs of similar magnitude would support system integration, data-model fusion, model development, decision support systems, visualization and communication.

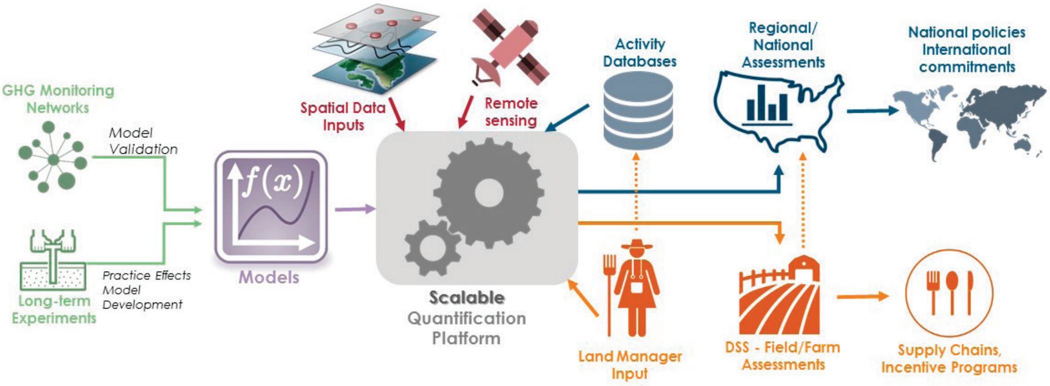

FIGURE 3.6 Conceptual design for a data-model platform for quantifying carbon removal to soils.

Demonstration

Forest Demonstration Projects

Conventional forestry practices have been implemented worldwide for decades, so demonstrations are readily available. One area requiring new demonstrations is the frontier technology of increasing preservation of harvested wood products, particularly, how to improve the disposal and collection processes of wood products after their useful life. This research is linked to the basic research needed to improve landfill design for for harvested wood product preservation. The cost for USDA and EPA to conduct this research is $1.5M/y for 3 projects for 3 years. Associated with the basic research of improving landfill design to improve preservation of harvested wood, it is necessary to implement several demonstration projects representing different environmental conditions to facilitate scaling up this new technology. The cost for this research done by USFS and EPA is $1.5 M/y for 3 projects for 3 years. Another promising activity requiring demonstrations of potential impacts on carbon removal is forest restoration, which has been described for fire-prone areas as increasing carbon removal in the long term as a result of short-term reduction in carbon stocks of overstocked stands; for areas converted from natural vegetation to unsustainably managed forests that prematurely lose ability to sequester carbon; and for degraded forests that would respond to interventions to improve regeneration and stocking. The cost for USFS and partners to conduct this research is $1.5M/y for 3 projects for 3 years.

Agricultural Systems Field Experiment Network

Field experiments to rigorously evaluate region-specific best management practices for soil carbon sequestration (and net GHG reductions), in comparison to conventional practices, should be established in a coordinated network across the major U.S. agricultural soil types, involving land-grant universities and other research institutions with the relevant expertise in ecosystem carbon and GHG dynamics. Sites selected should complement existing experimental sites in USDA Agricultural Research Service's (ARS) GraceNET and Long-term Agricultural Experiment networks and relevant sites within NSF's Long-Term Ecological Research (LTER) and National Ecological Observatory Network (NEON) programs. The new network should have a coordinated set of measurement protocols and methods, including whole system carbon balance (i.e., eddy covariance) and other GHG (e.g., N_2O and CH_4) flux measurements as well as precision soil carbon stock and stock change measurements. Data sharing and archiving to support modeling and meta-analysis should be priority and field sites should include significant extension, outreach, capacity building, technology transfer, and demonstration to provide information to producers, extension agents, crop consultants, agency personnel, and other stakeholders. Sites should be designed for the field experiments and demonstrations to run for a minimum of 12 years. This research should be conducted by land-grant universities and USDA at about 10-15 sites at a cost of $600K/y per site for a total of $6-9M/y.

Deployment

Forest Carbon Project Deployment

Although scientific uncertainty about the amount of carbon sequestered locally from improved forestry practices is low, uncertainty about far-field impacts caused by the long-term effects of climate change and the economic feedback is high. To reduce this uncertainty, the following research is needed:

(1) Improvement in economic models that estimate leakage (i.e., reduced harvest in one location causing deforestation in another) and the impact of converting cropland to forest on food prices. Biological research is also needed to develop understanding of the impacts of significant impacts of carbon removal on biodiversity and of safeguards to ensure a sustainable biosphere. This research and related costs are discussed in the section on the research agenda for integrated assessment modeling in Chapter 4.

(2) Improvement in LCA methods to evaluate substitution of wood products for other materials that could expand wood use, especially if these displace structural materials such as steel and cement, which require large carbon emissions to produce. Substituting wood for other material typically results in a net reduction of GHGs; however, tools to quantify the net reductions in GHGs are not readily available or validated. The research needs for LCA and related costs are discussed in Chapter 4.

(3) Social sciences research on how landowners respond to incentives and the utilization of Extension Service system at the land-grant universities, to reach more landowners and practitioners who work on small parcels of forest to improve the equity of participation in assistance programs that tend to favor larger landholders. Only a small percentage of forest landowners respond to incentive programs or price signals by changing land management practices. Very little research has been conducted on these topics (USDA and NSF; $1.0M/y for 3 projects over 3 years).

(4) Research on GHG and social impacts of reducing traditional uses of biomass for fuel, which involves households and small entities using wood biomass for heating and cooking. Globally, increasing durable wood products or increasing commercial use of biofuel could reduce consumption of biomass for traditional fuel use, which would have a ripple effect on types of energy supplied (USDA and NSF; $1.0M/y for 3 years).

(5) Social science research on responses to economic and behavioral incentives to reduce meat consumption and food waste. This research and related costs are included in the research agenda for integrated assessment modeling in Chapter 4 (BECCS).

Scaling Up Agricultural Carbon Sequestering Activities

Current adoption of existing best management practices for soil carbon sequestration are low (e.g., cover crop are used on <5 percent of U.S. cropland; Wade et al., 2015) and barriers to scale-up, including economic and behavioral changes (e.g., value proposition, risk management, motivation), information needs, and technology transfer, are poorly understood. Economic and behavioral research along with continuation and expansion of pilot emission reduction and carbon removal projects, such as through the USDA Natural Resource Conservation Service's Conservation Innovation Grants, can provide needed empirical knowledge on which barriers are most limiting and on how to design the most effective policies and education programs to promote agricultural carbon removal activities at scale.

Regional Life-Cycle Assessments

Any program to offer incentives to landowners for adopting carbon removal and storage should be preceded by a regional assessment of life cycle emissions, costs, co-benefits and negative impacts, including estimates of leakage and the degree of permanence, which can be undertaken by federal land management agencies (e.g., USDA Forest Service and USDA Agricultural Research Service) and/or university researchers, with a review of the findings by an independent scientific board. This research and related costs are discussed in the LCA section of Chapter 4.

Implementation of Terrestrial Carbon Sequestration

Policies that overcome potential barriers to developing robust research and adopting carbon removal and soil carbon sequestration for terrestrial NETs (cropland and forestland) may include several different mechanisms including (1) government subsidies to landowners to adopt carbon sequestering practices, similar to existing conservation payments in the Farm Bill, (2) carbon offset markets, in which land-based "carbon projects" market emission reductions/carbon sequestration to major GHG emitters participating in either voluntary or mandatory emission reductions (i.e., cap-and-trade), and (3) demand-side programs in which carbon removal activities are undertaken in response to demand for land-based consumer products that have a low carbon footprint. All three approaches currently exist. For government-based incentives (e.g., payments for practice adoption), the United States has a well-developed infrastructure of federal and state land management agencies and extension and outreach specialists to engage in implementation. For market-based systems, the voluntary GHG registries (e.g., VCS, ACR, CAR) and state agencies (e.g., CA Air Resources Board) have experience and governance structures that provide a starting point. New efforts on the part of companies to incentivize producers as part of sustainable or "low carbon" supply chain initiatives are at present much more fragmented, with the potential for double-counting and low transparency in the carbon removal activities actually undertaken. Hence institution building and development of governance structures to better engage the private sector in pursing demand-side carbon removal activities is a future need.

Land use and conservation practices that promote or encourage SCS for agricultural land and forest should be coupled with incentives and levels of regulations that encourage farmers, land managers, and landowners to adopt such practices. Current USDA conservation programs, such as the Conservation Stewardship Program, Environmental Quality Incentives Program, and Conservation Research Program, serve as good examples of cost sharing for implementing such practices. However, a set of incentives should be developed within the Farm Bill by linking conservation adoption and level of compliance to the level of improvement in soil carbon. The permanence of SCS and associated soil and ecosystem services co-benefits can be enhanced via financial incentives through government programs or as price premiums driven by industry seeking to develop more environmentally-friendly supply chains. Ultimately, the widespread adoption and long-term maintenance of working lands that place a high priority on SCS and reduced GHG emissions requires that they are as (or more) profitable to the farmer/rancher/forester as the conventional systems that they replace.

Barriers to the Implementation of the Research Agenda

For the recommended research agenda to achieve its goal and have lasting impact, certain barriers to adoption of carbon sequestering management practices must be overcome. Actions to lower these barriers include capacity building and robust educational programs through extension and outreach and other government and private entities to promote the carbon removal and SCS concept, research findings and technology transfer to end users; economic incentives to compensate for added costs or potential yield loss while transitioning to new management practices; and development of agronomists and specialists that can train and work with end users, to name few. However, a focus on the delivery and promotion of new technology alone will not be sufficient. These efforts should be coupled with social sciences research to better understand the drivers that lead to the fundamental changes in land management practices necessary to achieve terrestrial carbon removal at scale. The research agenda should include an integrated platform for cropland, grassland, and forestry projects such as with the NIFA Coordinated Agricultural Projects (CAP), where research, extension, and education are required components of funded proposals. In particular, the applied components of the research agenda (e.g., on-farm network and demonstration) would benefit from a multidisciplinary approach and collaboration between federal, state, and private agencies to achieve the goals of the research program. Development of relevant K-12 curricula could increase awareness about the practices that enhance carbon removal and soil carbon sequestration, including training opportunities for teachers, students, and the public at large. Such efforts may include hands-on demonstration of proven technologies, such as no-till, cover crop, residue management and agroforestry practices. Universities and USDA scientists can collaborate to develop and facilitate education and technology transfer through existing infrastructure and programs within land-grant universities and other public and private institutions.

SUMMARY

Terrestrial ecosystems can play a significant role in carbon dioxide removal and sequestration, through practices that increase the amount of OC stored in living plants, dead plant parts, and the soil. Please note that bioenergy with carbon capture and storage (BECCS), which also involves carbon removal via plant photosynthesis, is covered in Chapter 4 of this report.

Two suites of land management practices involving agriculture and forestlands are sufficiently mature, both scientifically and in practice, to materially increase carbon storage if widely deployed in the United States and globally. Options exist for inexpensive remote monitoring and verification of the practices that lead to carbon capture and storage, which, when coupled with data and model-based quantification of net carbon storage, can reduce the need for expensive on-site direct measurements of carbon on lands that adopt these practices.

Increasing the area of forested land through afforestation/reforestation creates a carbon sink ranging from 1.5 to 6.4 tC/ha/y for a period of 50-100 years or more. Changing forest management practices such as extending timber harvest rotations and improving stocking and productivity by restoring degraded forests could store an additional 0.2 to 2.5 tC/ha/y for several decades. Development of new technologies to increase the use of long-lived wood products as well as carbon burial schemes for harvested wood are options for increasing carbon removal potential from forests.

For cropland and grassland, many long-term experiments document increases of soil carbon in the range of 0.2-0.5 tC/ha/y (over time periods of 2-4 decades) from adopting conservation practices including more diverse crop rotations, use of cover crop, reduced tillage, and improved grazing system. Other changes in land use and management such as agroforestry or reestablishment of wetland and perennial vegetation on marginal lands can achieve increases in SOC stocks of more than 1 tC/ha/y. Additional frontier soil NETs include deep soil inversion and burial of carbon-rich topsoil, biochar amendment, and development of enhanced root carbon input crop phenotypes.

The committee estimates "practically achievable" carbon removal amounts. In other words, existing practices would be implemented at rates that do not require land-use conversion that would jeopardize food security and biodiversity of intact native ecosystems. These estimates are 0.6 Gt/y CO_2 from forestland and 0.25 Gt/y CO_2 in agricultural soils for the United States, and corresponding estimates of 9 and 3 Gt/y CO_2 for the world. Much of this CO_2 removal would be achieved for less than $50/t. If frontier NETs prove practical and economical, rates of carbon removal for both forests and agricultural soils could roughly double in size.

Finally, the mix of research needs is broad and includes basic research, measurement and monitoring technology, regionally representative demonstration projects, and barriers to deployment and scale-up.

CHAPTER FOUR

Bioenergy with Carbon Capture and Sequestration

INTRODUCTION

Combining bioenergy production with carbon capture and sequestration can lead to net negative emissions as carbon stored by photosynthesizing biomass growth is sequestered rather than released to the atmosphere (IEA, 2011). The concept was first developed by Obersteiner et al. (2001) as a backstop climate risk measure, and by Keith (2001) as a potential mitigation tool. Since then, biomass energy with carbon capture and sequestration (BECCS) has come to be viewed as a key carbon dioxide removal approach to keep global atmospheric CO_2 concentrations below 500 ppm and avoid catastrophic climate change. BECCS is largely used by integrated assessment models (IAMs) because its cost is low relative to other low carbon technologies and because the modules to represent other carbon dioxide removal technologies are undeveloped (e.g., direct air capture and soil carbon management). In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) concludes, based on a literature review of mitigation scenarios developed with IAMs, that many scenarios that limit warming to 2°C select BECCS as the lowest cost option to reach the temperature objectives for the second half of the century (high confidence) and that BECCS plays an important role in many low-stabilization scenarios (with limited evidence and medium agreement) (Fisher et al., 2007b). The International Energy Agency climate change models suggest that at least 2 Gt CO_2 per year removal by BECCS should be implemented by 2050 to keep global temperature rise below 2°C (IEA, 2009). To put this in perspective, 1 Gt dry biomass is roughly equivalent to 1.4 Gt CO_2 and 14 exajoules (EJ) primary energy, and the United States annually emits about 6.5 Gt CO_2 and consumes slightly more than 100 EJ of primary energy. Yet many policymakers and academics are not aware of the pervasive and pivotal role that BECCS plays in climate change mitigation pathways despite being in its infancy (Anderson and Peters, 2016).

BECCS typically refers to the integration of trees and crops that extract CO_2 from the atmosphere as they grow, the use of this biomass in power plants, and the application of carbon capture and sequestration via CO_2 injection into geological formations. This chapter entails a much broader scope of biomass energy–based carbon removal pathways, including (1) biomass combustion to thermal and electrical power with carbon capture and sequestration (traditional BECCS), (2) biomass thermochemical conversion to fuel with biochar soil amendment, and (3) biomass fermentation to fuel with carbon capture and sequestration (Figure 4.1). The scope of this chapter examines biomass energy in the forms of electricity, heat, and fuels, and capture in the forms of CO_2 and biochar. Compression, transportation, and sequestration are covered in Chapter 7.[1]

This chapter begins with a review of the various biomass energy–based carbon removal pathways and their commercial status. This is followed by an assessment of their removal and sequestration potential based primarily on biomass supply potential and process economics. The chapter closes with the committee's proposed research agenda for biomass energy–based carbon dioxide removal technology.

BACKGROUND

Approach Description

This section reviews the various technological pathways for bioenergy with carbon capture and sequestration by dividing the pathways into four steps: (1) biomass production, (2) biomass transportation, (3) biomass conversion, and (4) carbon capture (Figure 4.2).

Biomass Production

Biomass feedstock may come from forest management (e.g., tree stems, branches, bark, logging residues, sawmill waste), agriculture (e.g., purposed-grown feedstock, crop residues), algae cultivation, or collection of municipal organic solid waste. Biomass sequesters atmospheric CO_2 while growing, leading to an initial negative emission. The production and collection of biomass feedstock involve several activities such as seeding, fertilizer and pesticide production and spreading, tilling, logging roads, and tree harvesting. Energy used in these activities is part of the life cycle assessment (LCA).

The total managed land area in the United States potentially available for biomass production is nearly 900 Mha, though much of this land is already used for

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[1] Given that costs for compression, transportation, injection, and storage for CO_2 captured both through BECCS and direct air capture are assumed to be approximately the same, the report discusses them once in Chapter 7 on Geologic Sequestration and again in Appendix F.

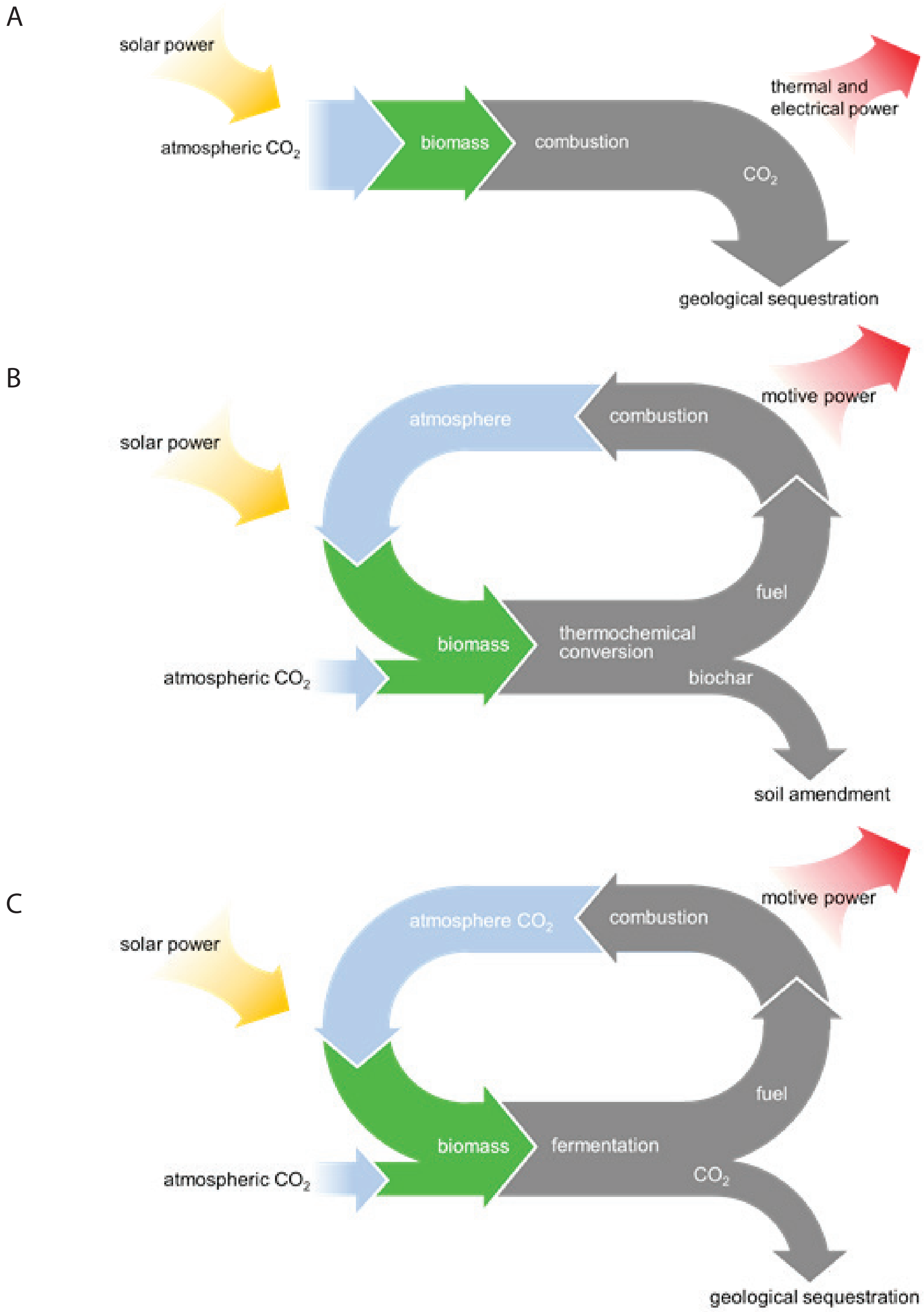


FIGURE 4.1 Generic biomass energy-based carbon dioxide removal pathways: a) biomass-to-power with carbon capture and sequestration, b) biomass-to-fuel and biochar, and c) biomass-to-fuel with carbon capture and sequestration. Note that these closed carbon cycles are idealistic and that in reality carbon leakage could occur. For a more detailed discussion of leakage, see Chapter 7.

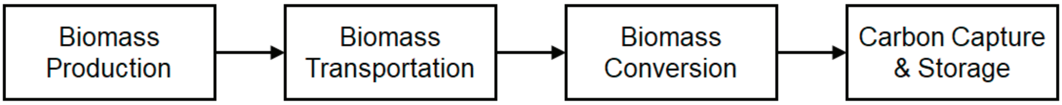


FIGURE 4.2 Biomass energy carbon dioxide removal and sequestration steps.

commodities such as food, forage, and fiber (Table 4.1). However, the biomass supply could be increased on most of this land without changing land use. An important caveat is that there is only one land base; therefore, in this study, the land base for bioenergy is the same land base potentially available for forestry and agriculture carbon dioxide removal approaches. The discussion of how land use requirements for BECCS and other terrestrial approaches interact is found in Chapter 3.

On forestland, annual biomass production exceeds current harvest by about 70 percent (Smith et al., 2007) or 204 Mt/y dry biomass. Some of this could be harvested for bioenergy, but this would reduce the forest carbon stock and sink strength, which in turn would reduce the carbon removal benefit from forests. However, on forestland that is currently harvested, a significant amount of logging residue is not currently utilized, and some of this is readily available to increase bioenergy supply. Constraints on utilization of existing logging residue include the economic feasibility of removing and transporting the biomass and the potential impacts on ecosystem productivity. Many U.S. states have regulations requiring a certain amount (about 25 percent) of logging residue to be left on site to sustain productivity and wildlife habitat (Janowiak and Webster, 2010; Venier et al., 2014). How the residues have been treated (e.g., left

TABLE 4.1 U.S. Managed Land Area by Land-Use Category in 2015 (mega-hectares)[a]

Category[b]	United States
Forests	293
Croplands	163
Grasslands	325
Settlements	43
Wetlands	42
Other Land	23
Total	890

[a] Data from EPA, 2017.

[b] Defined by IPCC and the U.S. EPA.

to decompose, burned, or used in a different wood product) and the rate of on-site decomposition also affect the carbon removal benefit.

Croplands present opportunities to increase use of agricultural residues such as corn stover, much of which is currently not utilized. Settlements produce significant quantities of organic waste, much of which could be used to increase supply of biofuel. One of the more promising and potentially productive options would be to grow energy crops on land that is considered "marginally productive" for crops. There is a significant amount of marginal land in the United States and globally that could be converted to energy crops without affecting production of other commodities (see more details in Chapter 3). A good estimate of such land for the United States is the amount of farmland enrolled annually in the Conservation Reserve Program, which typically exceeded 8 Mha/y before area limits were established (Mercier, 2011).

The productivity of biomass supply alternatives is highly variable by geography and biomass source. Excluding wastes and residues, some categorical, as well as several specific bioenergy crop productivity, estimates are shown in Table 4.2. These data highlight the variability in productivity within and between regions as a result of climate, site factors, and feedstock differences and provide a basis for the increase in biomass cost as the total biomass supply increases.

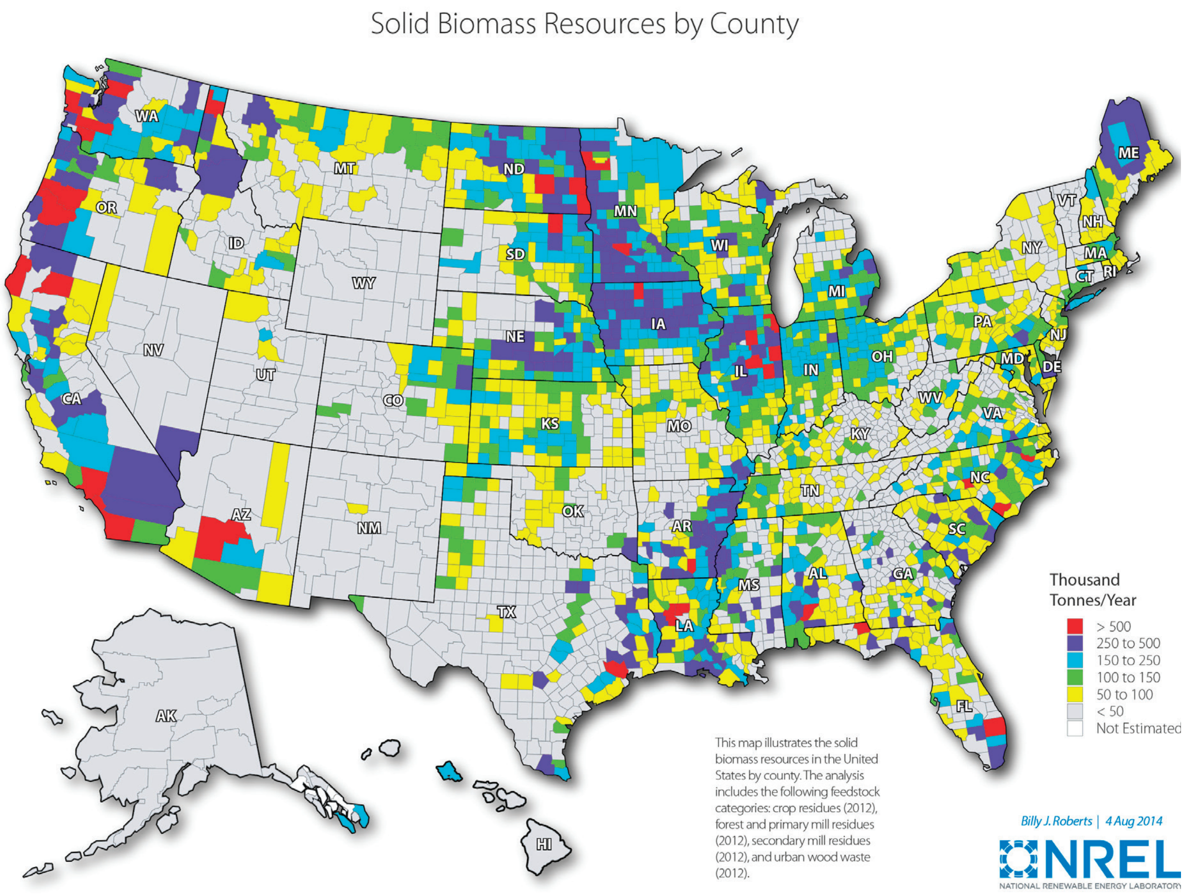
Biomass Transportation

Biomass must be transported from the source to the conversion facility or end user, where it will be converted to heat, electricity, or other fuels. This fuel must then be distributed to end users. A map of the distribution of biomass resources across the United States (Figure 4.3) shows that the east and west coasts and center of the United

TABLE 4.2 Productivity of Selected Bioenergy Crops by Region (tonnes per hectare)

Crop Type/ Species	Northeast	Southeast	Delta	Corn Belt	Lake States	Plains States
Perennial grasses	9.0-16.8	7.8-21.3	6.7-15.7	9.0-15.7	1.8-11.2	4.5-14.6
Woody crops	11.4	11.2-12.3	—	7.8-13.4	7.8-13.4	7.8-13.4
Switchgrass	10.3-16.4	10.5-20.8	13.7-21.3	12.3-19.5	6.0-7.4	3.8-19.9
Poplar	9.9-13.2	9.0-14.8	10.5-14.6	10.3-15.0	8.3-13.0	5.8-12.5
Willow	8.5-16.4	8.5-16.8	10.8-12.5	8.7-18.4	8.3-15.9	3.1-13.9
Miscanthus	14.3-20.4	13.0-19.3	16.1-23.1	17.7-25.1	11.9-23.5	8.5-25.1

SOURCE: DOE, 2011, 2016.



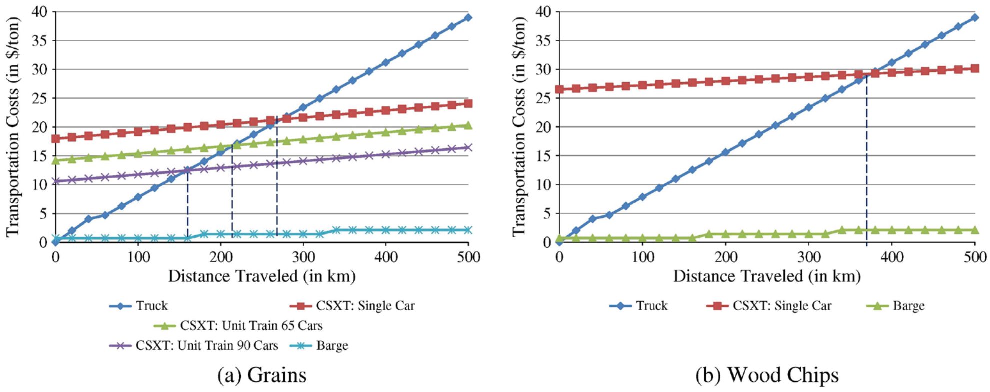
This map illustrates the solid biomass resources in the United States by county. The analysis includes the following feedstock categories: crop residues (2012), forest and primary mill residues (2012), secondary mill residues (2012), and urban wood waste (2012).

FIGURE 4.3 A map of solid biomass resources by county across the United States.
SOURCE: NREL: https://www.nrel.gov/gis/images/biomass_2014/national_biomass_solid_total_2014-01.jpg.

States have the most plentiful resources, while regions in between have far sparser supplies. Thus, biomass would have to be transported over substantial distances for utilization in those regions. Even in the regions of more plentiful biomass supply, where shorter transportation distances can be expected, costs and emissions incurred by transportation can be substantial.

The results of an assessment of transportation costs for densified biomass, summarized in Figure 4.4, show that barge is by far the least expensive transportation mode for long-distance domestic transportation where available (Gonzales et al., 2013). Barge access is quite limited, however, and the remaining options include truck and rail. Truck transportation is less expensive for relatively short distances, and break-even distances are presented in Figure 4.4. Furthermore, truck transportation can take advantage of the widespread road network in the United States, as compared to the more limited rail network. At longer distances, rail is less expensive than truck transportation.

In addition to cost, emissions associated with biomass transportation can be significant and should be accounted for in assessments of net carbon emissions from biomass utilization. LCAs of greenhouse gas (GHG) emissions in bioenergy production estimate emissions from biomass transportation based on shipment method (road, rail, or sea) and distance. Figure 4.5 presents an example of these estimates for dry biomass transport by truck, train, or sea freight (Beagle and Belmont, 2016). Results



(a) Grains

(b) Wood Chips

FIGURE 4.4 Transportation costs for (a) grains and (b) wood chips from Midwest to East and Southeast United States.
SOURCE: Gonzales et al., 2013.

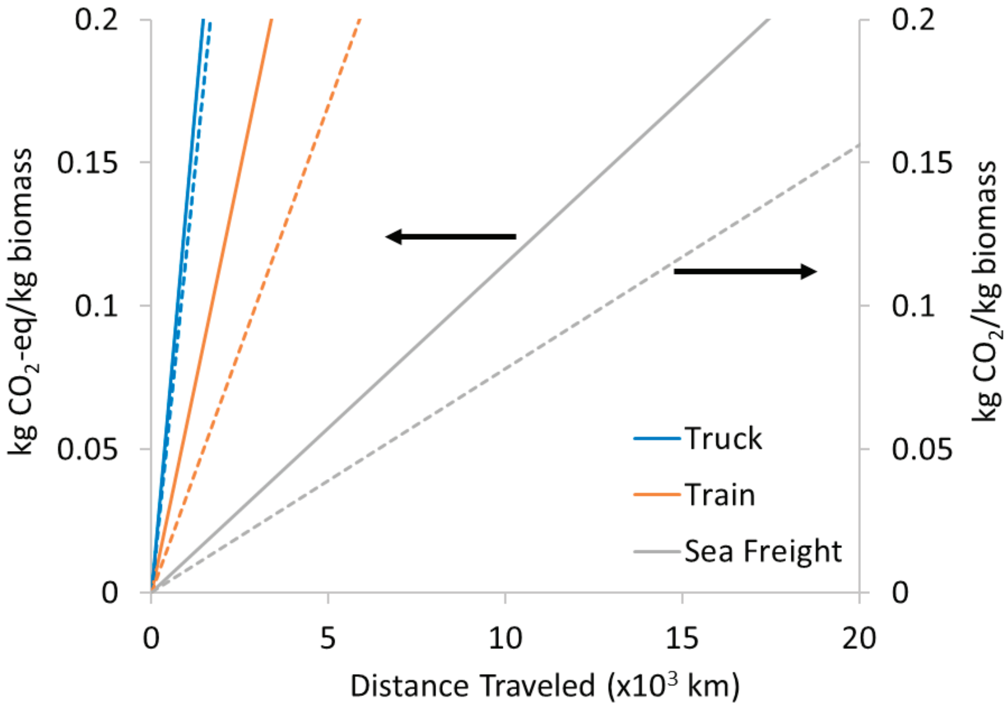


FIGURE 4.5 CO_2 and CO_2e emissions per dry biomass produced as a function of transportation distance by road, rail, or sea.
SOURCE: Beagle and Belmont, 2016.

show that truck transportation has significantly higher emissions per kilometer than train and sea freight.

Biomass Conversion

Figure 4.6 provides a detailed illustration of the many potential biomass-to-energy technologies, which are at varying technology readiness levels (TRLs). This section describes two broad approaches to biomass conversion.

Thermochemical. Several thermochemical and biological routes for the conversion of biomass to energy have been demonstrated and implemented. Thermochemical routes broadly include pyrolysis, hydrothermal liquefaction, gasification, and combustion (Goyal et al., 2008). Pyrolysis approaches heat biomass in the absence of air (oxygen-deficient or anoxic) or in the presence of hydrogen (hydropyrolysis) to produce liquids and gases that can be upgraded to fuels or directly combusted and solid

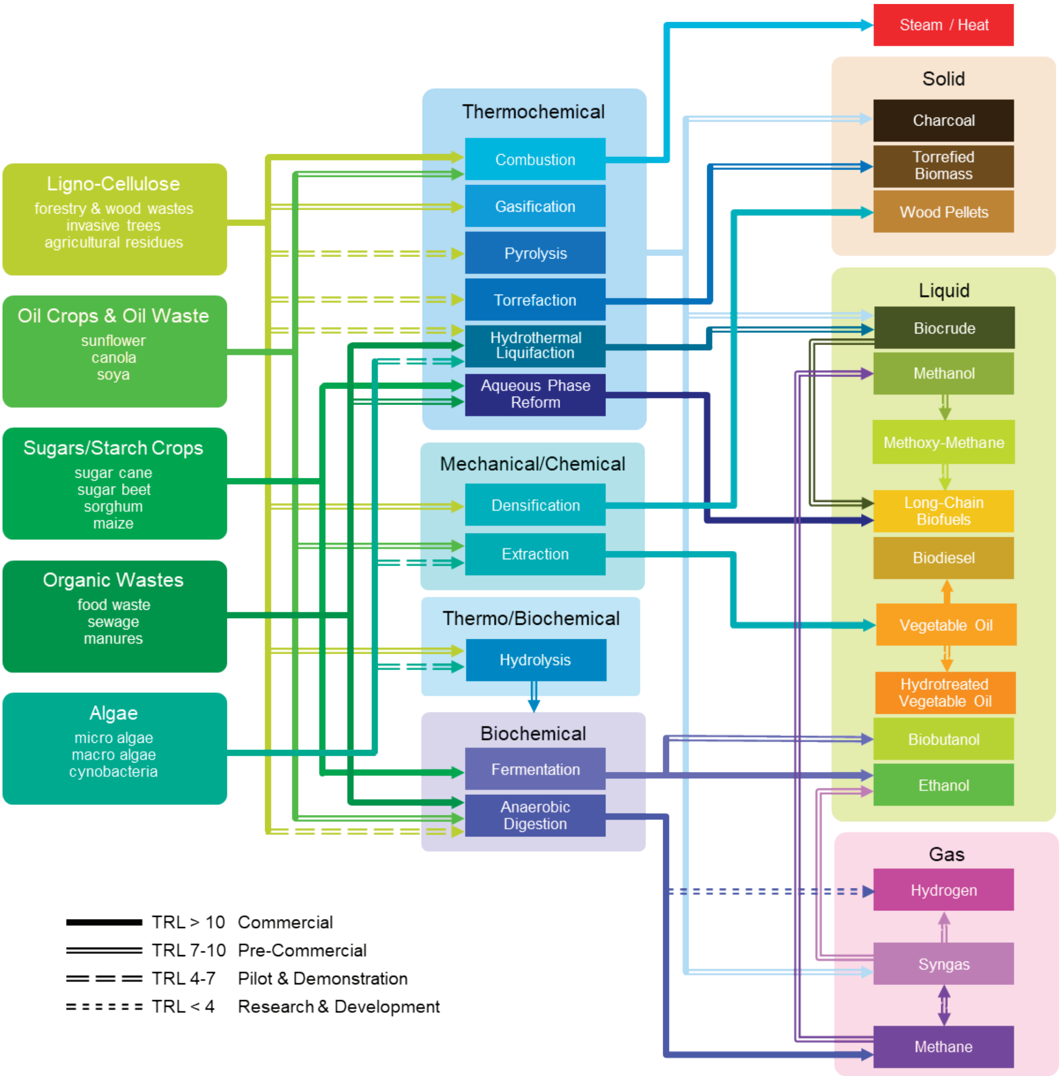


FIGURE 4.6 Biomass conversion pathways and technology readiness levels (TRLs). (Adapted from Stafford et al., 2017).

carbon-rich biochars that can be combusted, gasified, or sequestered as a soil amendment.[2] Pyrolysis may proceed at high heating rates and short residence times to favor liquid yields (fast pyrolysis), or a slow heating rates and long residence times to favor solid carbon production (slow pyrolysis or carbonization).

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[2] The use of biochar as a soil amendment is discussed in Chapter 3.

Hydrothermal liquefaction converts biomass at elevated temperatures and under high pressure steam to predominantly liquid products. Gasification, in contrast to pyrolysis and liquefaction, uses an oxidant (e.g., steam, air, or CO_2) to partially oxidize biomass to produce synthesis gas, composed of CO and H_2 that can then be converted to liquid fuels via thermocatalytic processes, such as Fischer-Tropsch and methanol-to-gas (MTG); or directly combusted for heat and/or power generation. Finally, combustion uses air or pure oxygen gas to completely oxidize biomass to produce heat for direct use or for power generation.

Biological. In addition to thermochemical biomass-to-fuel conversion routes, several biological pathways produce liquid and gaseous fuels (Antoni et al., 2007). Biological routes harness anaerobic digestion and fermentation to produce hydrogen, methane, and alcohol (e.g., ethanol) fuels. These biologically derived fuels can be burned directly for heat and power or upgraded to other fuels. An additional microbial route to biofuel production is the use of oil-producing microbes to directly generate biofuel precursors, such as the use of algae via photosynthesis.

Carbon Capture and Sequestration

The main carbon capture and sequestration pathways under consideration for biomass energy carbon removal are (1) biomass combustion or fermentation with CO_2 capture, compression, and transportation to a geological site for long-term sequestration and (2) biomass conversion to fuels with biochar (solid carbon) co-production that can be stored long-term as a soil amendment (see Chapter 3).

Carbon Capture. CO_2 capture technologies for biomass thermal and electrical power generation are generally the same as those currently under development for conventional fossil fuel power plant carbon capture and sequestration. Broadly, these technologies fall within four main categories: post-combustion, pre-combustion (or gasification), oxy-combustion, and chemical looping (Figure 4.7). While active research is ongoing in all of these categories for coal power plants, the different approaches vary significantly in technologic maturity. Table 4.3 presents estimated TRLs, carbon capture work, exergy efficiencies, levelized costs of electricity (LCOEs), and carbon capture costs for the different coal power plant carbon capture approaches. The fundamental challenge with carbon capture is achieving a pure stream of CO_2 for sequestration that involves either separating oxygen from air before combustion or CO_2 from power plant exhaust after combustion. The exergy efficiency, calculated from ideal (minimum) work for separating gases over the estimated actual work to separate CO_2, is used to provide a reference point for assessing the overall energy requirement for

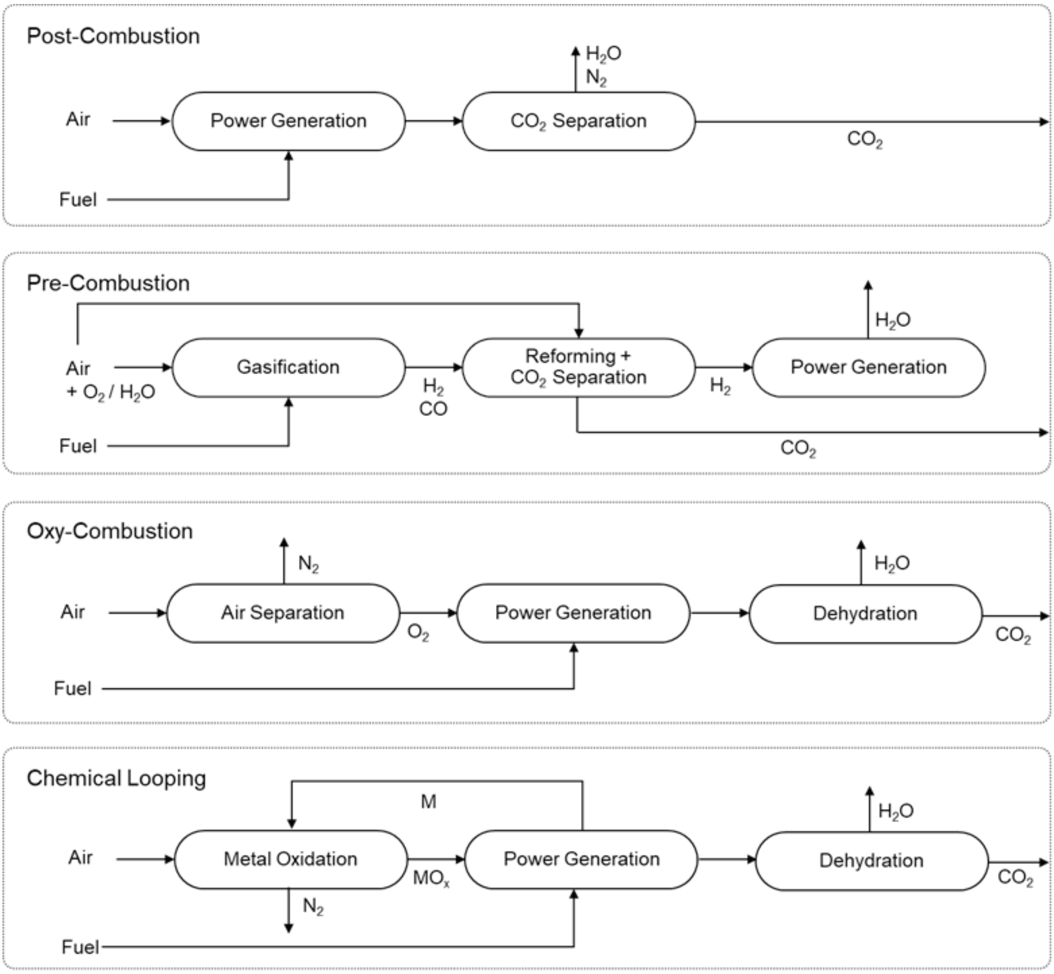

FIGURE 4.7 Simplified block diagrams of coal or biomass power with carbon capture approaches: post-combustion, pre-combustion, oxy-combustion, and chemical looping carbon capture.

carbon capture and benchmarking the state-of-the-art relative to what is theoretically possible. These values are only for CO_2 *captured* cost (energetic and financial), whereas CO_2 *avoided* cost includes the compression, transport, and sequestration of the CO_2 including the extra power and generated CO_2 needed to carry out these operations. Carbon capture from fermentation processes, such as those used to produce ethanol, can utilize the same technology that is being developed for carbon capture in fossil fuel plants. CO_2 is produced as a byproduct of the fermentation process itself, as well as from the power plant that supplies electricity and heat to the fermentation process. Therefore, both sources are candidates for CO_2 capture. In the United States,

TABLE 4.3 Coal Power Plant Carbon Capture Approach and Estimated CO_2 Capture Work, Exergy Efficiency, and Cost for Different Carbon Capture Approaches

Carbon Capture Approach	Power Plant Type	TRL	CO_2 Capture Work (GJ/t)	Exergy Efficiency (percent)	LCOE ($/MWhe)	CO_2 Capture Cost ($/t)	References
Post-Combustion	SCPC	9	1.0-2.6	8-21	94-130	36-53	Rubin et al., 2015
Pre-Combustion	IGCC	7	1.1-1.6	12-18	100-141	42-87	Rubin et al., 2015
Oxy-Combustion	SCPC/ USC	7	1.3-1.7	12-15	91-121	36-67	Rubin et al., 2015
Chemical Looping	CDCL	6	~ 2.1	~ 9	~ 101	?	Fan, 2012

NOTES: Exergy efficiency is the minimum work for carbon capture (0.2 GJ/tCO_2) over the process exergy. TRL, technology readiness level; LCOE, levelized cost of electricity; SCPC, supercritical pulverized coal; IGCC, integrated gasification combined cycle; USC, ultra-supercritical; and CDCL; coal direct chemical looping.
SOURCE: Bui et al., 2018.

biorefineries currently emit about 45 Mt/y CO_2 from fermentation, of which 60 percent could be captured and compressed at a cost estimated to be less than \$25/t CO_2 (Sanchez et al., 2018).

Biochar Soil Amendment. The thermochemical conversion of biomass to fuels can produce 25-45 percent by mass biochar (solid carbon) as a byproduct, depending on the feedstock and process conditions (temperature, pressure, partial pressures, and residence times). The fraction of biochar production is important because it helps determine whether some biomass-to-fuels pathways are actually carbon negative (Del Paggio, personal communication, 2017). Biochar soil amendment has been proposed as a promising path for long-term carbon removal strategy; however, questions remain about the long-term stability of biochar in soil environments. Proponents claim that biochar application reduces the burden on farmers in several ways: less fertilizer is needed because biochar absorbs, stores, and slowly releases nutrients such as phosphorus to plants and subsequently to the environment; biochar improves soil moisture retention, securing the crops against drought; farmers spend less on seeds as germination rates increase; biochar reduces the methane emissions from paddy fields and farmyard manures; it increases the soil microbes and other soil-life density; it lessens the hardening of soils; it supports better growth of roots and helps in reclaiming degraded soils (Jeffery et al., 2011). For additional details see Chapter 3.

COMMERCIAL STATUS

Biomass-fueled power generation is commercially deployed across the United States and the world, although no biomass power plants are coupled with carbon capture and sequestration (CCS). Of the 4,000 TWh of electricity generated in the United States in 2016, only 40 TWh was from wood-derived fuels and 22 TWh was from other biomass sources, including municipal solid waste, agricultural byproducts, and other biomass (EIA, 2017d).

Large-scale biological biomass-to-fuel technology has been deployed commercially, most notably in the production of approximately 370 million barrels of ethanol (EIA, 2017c). Table 4.4 presents select biomass-to-fuel pathways and their TRLs and developers. Few of these projects have coupled the fuel production process with CCS. Among these, the largest is the Illinois Industrial Carbon Capture and Storage (IL-ICCS) project, where pure CO_2 gas is formed as a byproduct of fermentation for ethanol production at an Archer Daniels Midland (ADM) plant near Decatur, Illinois, and is collected and injected into the nearby Mt. Simon Sandstone saline formation. This project plans to capture 0.9-1.0 Mt CO_2 annually and began CO_2 injection in 2017. This project follows on the completion of the Illinois Basin-Decatur Project, which captured and injected CO_2 from the ADM plant to the Mt. Simon formation at a lower rate for 3 years. Notably, the ADM emits approximately 5 Mt/y CO_2, making the process net carbon positive because of CO_2 emissions from the power plant. However, techno-economic studies have shown that such processes can be carbon negative if CCS is applied across the entire chemical plant, including the fermenter and power generation unit.

Additionally, biochar production is now a commercial activity with many producers located throughout North America. According to a recent survey commissioned by the U.S. Forest Service (Draper et al., 2018) an estimated 39,000 to 77,000 t/y biochar are produced in the United States, and an additional 1,900 to 7,300 t/y are produced in Canada. Current biochar sales prices are around $1,800/t, with most consumers reportedly using it as a soil amendment to modify texture, increase porosity, improve water management, and increase soil carbon. To increase market size, biochar producers are actively seeking biochar certification as an animal feed supplement, as is done in Europe.

TABLE 4.4 Select Biofuel Processes, Developers, and Technology Readiness Levels (TRLs)

Feedstock	Process	Product	Developer	TRL
Algae	Hydrothermal liquefaction	Liquid hydrocarbons	PNNL/Genifuels	6
	Fermentation	Ethanol	KIIT	6
	Extraction	Biodiesel	RIIHL	7
Sugar/Starch	Anaerobic digestion	Methane	(many)	10
	Fermentation	Butanol	Green Biologics	8
	Fermentation	Ethanol	(many)	10
	Aqueous phase reforming	Liquid hydrocarbons	Virent/Shell	3
Organic Waste	Aqueous phase reforming	Liquid hydrocarbons	Virent	3
	Hydrothermal liquefaction	Liquid hydrocarbons	PNNL/Genifuels	4
	Anaerobic digestion	Methane	(many)	10
	Gasification	Ethanol	Enerkem	8
	Gasification	Ethanol	LanzaTech	8
	Hydropyrolysis	Liquid hydrocarbons	CRI/GTI	6
Oil Crops/Waste	Anaerobic digestion	Methane	(many)	10
	Extraction	Vegetable oil	(many)	10
	Extraction	Biodiesel	(many)	10
Lignocellulose	Hydrothermal liquefaction	Biocrude	Licella	5
	Densification	Pellets	many	10
	Torrefaction	Torrefied biomass	Arbaflame, SINTEF	8
	Anaerobic digestion	Methane	(many)	9
	Fermentation	Butanol	Green Biologics	9
	Fermentation	Ethanol	(many)	10
	Pyrolysis	Charcoal/biochar	(many)	10
	Pyrolysis	Liquid hydrocarbons	(many)	5
	Hydropyrolysis	Liquid hydrocarbons	CRI/GTI	8
	Gasification	Liquid hydrocarbons	(many)	7

NOTE: CRI, CRI Catalyst Company, Shell Group; GTI, Gas Technology Institute; KIIT, Korea Institute of Industrial Technology; PNNL, Pacific Northwest National Laboratory; RIIHL, Reliance Industrial Investments and Holdings Ltd.

SOURCE: Adapted from Stafford et al., 2017 and IRENA, 2016.

IMPACT POTENTIAL

Availability of biomass feedstock is a critical issue when assessing the potential role of BECCS to mitigate climate change, and a wide range of values are available in the literature with order of magnitude uncertainties (Azar et al., 2010; Slade et al., 2014). For instance, Berndes et al. (2003) estimated the total annual contribution of biomass in the future global energy supply to be between 100 EJ and 400 EJ in 2050 based on a review of 17 published studies. High uncertainties associated with land availability, energy crop yields, and the future availability of waste, forest wood, and residues from forestry and agriculture are the main reasons for this wide range of values (Slade et al., 2014). In this section, the Committee presents an estimate of biomass potential for the United States and the world, associated negative CO_2 flux, potential radiative impacts and costs for bioenergy with carbon capture.

Carbon Flux

Using biomass availability data (summarized in Table 4.5 and assumptions discussed below), the committee estimated the economically feasible (i.e., without significant impacts on current land and biomass use) BECCS CO_2 flux potential for the United States. The economically feasible lower bound is 522 Mt/y CO_2 and is based on the following assumptions:

- No energy crops are utilized for BECCS. Although high levels of BECCS deployment depend on productivity increases of about 1 percent annually, energy crops are eliminated from the lower-bound estimate because energy crop production and utilization is not widespread and significant concerns exist regarding impacts on climate and food security from increasing energy crop production. Indeed, as shown by Heck et al., 2018, the potential for BECCS from dedicated bioenergy plantation is marginal if we use precautionary guardrails to stay within planetary boundaries for nonclimate impacts such as biodiversity or freshwater use.
- Agricultural byproducts are included at an amount equal to the difference between economically feasible production in 2040 and the current utilization level to avoid displacing demand and creating new needs that might lead to land burden (annual flux = 113 Mt/y CO_2).
- Economically recoverable and currently unused forestry logging residues and other wood wastes are included based upon 2040 availability. Whole-tree biomass from thinnings and fuel treatments, and wood currently used for home and industry heating, are not included because barriers to these sources

TABLE 4.5 Estimated U.S. Dry Biomass Potential and Equivalent CO_2 Fluxes (Mt/y)

Source	Current Use	2017				2040			
		Technical Potential		Economically Feasible		Technical Potential		Economically Feasible	
	Biomass	Biomass	CO_2 Flux	Biomass	CO_2 Flux	Biomass	CO_2 Flux	Biomass	CO_2 Flux
Agricultural Byproducts	**130**	**154**	**269**	**125**	**218**	**219**	**382**	**195**	**339**
Agricultural residues	—	106	185	94	164	171	298	161	280
Agricultural wastes	—	48	84	31	54	48	84	34	59
Energy Crops	**0.087**	**503**	**875**	**—**	**—**	**503**	**875**	**373**	**649**
Switchgrass	—	—	—	—	—	—	—	146	254
Miscanthus	—	—	—	—	—	—	—	145	253
Biomass sorghum	—	—	—	—	—	—	—	17	30
Energy cane	—	—	—	—	—	—	—	0	0
Non-coppice	—	—	—	—	—	—	—	41	71
Coppice	—	—	—	—	—	—	—	24	41
Forestry	**132**	**332**	**609**	**124**	**228**	**332**	**609**	**122**	**225**
Logging residues	—	43	78	16	30	43	78	19	35
Whole-tree	—	143	263	64	117	143	263	55	102
Other wood wastes	—	146	268	44	82	146	268	48	88

TABLE 4.5 Continued

Source	Current Use	2017				2040			
		Technical Potential		Economically Feasible		Technical Potential		Economically Feasible	
	Biomass	Biomass	CO_2 Flux	Biomass	CO_2 Flux	Biomass	CO_2 Flux	Biomass	CO_2 Flux
Organic Waste	**36**	**259**	**240**	**259**	**240**	**309**	**286**	**309**	**286**
Municipal solid waste	30	203	166	203	166	242	198	242	198
Construction and demolition	—	46	68	46	68	54	81	54	81
Sewage and wastewater	6	10	6	10	6	12	7	12	7
Total	**298**	**1248**	**1993**	**508**	**686**	**1363**	**2152**	**999**	**1499**

NOTES: Includes current levels of biomass utilization, lower- and upper-bound dry biomass potentials for different feedstock types, and associated CO_2 flux potentials, assuming all biomass carbon content is captured and sequestered regardless of biomass conversion path.

SOURCES: DOE, 2016; EPA, 2016c; Rose et al., 2015; Seiple et al., 2017; USDA, 2014.

are expected, such as concerns about effects on intact forests (annual flux = 123 Mt/y CO_2).

- Organic wastes, the majority of which consist of municipal solid waste, are included based upon 2040 availability (annual flux = 286 Mt/y CO_2).

The U.S. economically feasible upper-bound BECCS CO_2 flux potential is estimated to be 1,500 Mty CO_2 based upon all available agricultural byproducts, energy crops, forestry waste and byproducts, and organic waste. This flux corresponds to the total carbon content of available biomass and does not account for losses and other GHG emissions throughout the supply chain. It also does not take into account the land demands or conflicts that might arise at maximum flux values. Therefore, it is not considered as safely achievable.

The global upper-bound BECCS CO_2 flux potential is estimated to be 10-15 Gt/y $CO_2$by 2050 according to the IPCC (IPCC, 2014b). The lower bound flux is assessed using a reduction factor based upon the maximum versus lower bound U.S. fluxes. This approach assumes that globally available biomass has a similar composition and source distribution as U.S. biomass supply and is subject to similar restrictions. While this assumption is likely flawed, it provides a coarse assessment of global flux potential. The U.S. lower bound range is approximately 35 percent of the maximum potential flux; thus, the global lower bound BECCS CO_2 flux potential is estimated to be 3.5-5.2 Gt/y CO_2 by 2050.

Agricultural Byproducts

Agricultural byproducts include residues and waste streams, as defined and summarized in the Department of Energy's (DOE's) *2016 Billion-Ton Report* (2016). That report also provided current consumption of all agricultural byproducts for energy production based on 2014 Energy Information Administration (EIA) data, including the byproducts used (9.5 Mt) for annual heat and power production, as well as the substantially larger amounts of agricultural biomass that is used each year for fuel and bio-based chemical production (approximately 115 Mt and 5.3 Mt, respectively). While carbon composition of agricultural residues can vary, an average carbon content of 47.5 percent by mass was used to evaluate CO_2 production.

Agricultural Residues. Agricultural residues include corn stover, wheat straw and sorghum, and oat and barley residues. Technical potential is defined in this report as the total resource available, and availability in the years 2017 and 2040 were estimated from the agricultural residues available at $88 t dry biomass ($80 per short ton), based on DOE (2016) under a base case scenario of 1 percent annual growth in yield.

These quantities were used as reasonable estimates of total availability because the production curves presented in the report show minimal increase in potential production with increase in farmgate price above \$88/t and up to \$110/t. The economically feasible quantities of agricultural residues presented in Table 4.5 were gathered from DOE (2016) for years 2017 and 2040 under the scenario of \$66/t farmgate price and 1 percent annual growth.

Agricultural Waste Streams. Agricultural waste streams include sugarcane bagasse and trash, soybean hulls, rice hulls and straw, grain dust and chaff, orchard and vineyard prunings, cotton gin trash and field residue, and animal manure. Although animal fats and yellow grease were also included in the agricultural waste resources identified in DOE (2016), they were not included in total agricultural waste stream assessment in this report because their likely utilization pathway is the production of biodiesel. Although biodiesel displaces fossil-derived fuels, neither of the carbon negative pathways identified in this report (combustion with CO_2 capture or pyrolysis with biochar sequestration) are achieved via biodiesel. Technical potential and economic feasibility were estimated for years 2017 and 2040 from data in the DOE (2016) report, where economic feasibility under the scenario of \$66/t farmgate price and 1 percent annual growth was used in this report.

Energy Crops

Current production for herbaceous energy crops comes from the most recent U.S. Department of Agriculture (USDA) census (USDA, 2014) as presented in DOE (2016). On the one hand, this value may be overestimated because it includes nonenergy uses such as animal bedding. On the other hand, it might be underestimated because producers often do not report planting of unique crops because they are not enrolled in federally subsidized programs or the crops are grown on nonprivate agricultural lands such as public universities. However, this value is so low that a potential under- or overestimation is probably negligible.

Current production for woody energy crops also comes from the most recent USDA census (USDA, 2014). The value available on the USDA website is in acres of crops for short-rotation woody crops. This value has been converted into annual production (Mt/y) by multiplying the acres of crops by the average dry biomass yield per acre (t/acre). The average yields are the mean region-specific yields for poplar and willow crops from DOE (2016).

Theoretically, the technical potential for biomass production from energy crops is very high because all crops in the United States could be converted to energy crops.

However, this would be a very unrealistic scenario. Therefore, a very rough estimate of the current technical potential has been calculated, considering that the difference between current total croplands and harvested croplands according to USDA (2014) could be cultivated as energy crops. In the USDA census, total croplands include "cropland harvested, other pasture and grazing land that could have been used for crops without additional improvements, cropland on which all crops failed or were abandoned, cropland in cultivated summer fallow, and cropland idle or used for cover crops or soil improvement but not harvested and not pastured or grazed." This area was then converted into dry production per year (Mt/y) by multiplying it by the average yield (t/acre) for all six energy crop types presented by DOE (2016).

Economically feasible biomass productions are detailed for each type of biomass assessed in DOE (2016), that is, switchgrass, miscanthus, biomass sorghum, and energy cane for herbaceous crops and non-coppice (poplar, pine) and coppice (willow, eucalyptus) for woody crops. They are taken from the 2016 *Billion-Ton Report* for a 1 percent annual yield increase and a biomass price at farm gate of less than $66/dry biomass. Achieving this 1 percent annual yield increase would require research to genetically modify herbaceous crops and develop silvicultural systems that target biomass production rather than wood volume or quality (Dietrich et al., 2014; Lotze-Campen et al., 2010; Robison et al., 2006). The DOE (2016) assumes agricultural lands to stay constant over the years. Therefore, additional energy crops replace other types of current crops such as food crops. In 2040, 8.3 percent of agricultural lands are devoted to energy crops under the 1 percent annual yield increase and the $66/dry biomass scenario. There are no economically feasible production values for 2017 in DOE (2016) because of the constraints included in the model, such as that all agricultural biomass feedstock comes from residues.

The annual CO_2 flux potential was calculated based on a 47.5 percent carbon mass content in dry biomass. Indeed, Schlesinger and Bernhardt (1991) have found that dry biomass carbon content is almost always between 45 percent and 50 percent by weight. Therefore, the mean value was used. This is an estimation of the amount of CO_2 sequestered from the atmosphere during biomass growth that could then be stored using BECCS technologies. However, this is not an estimation of the net potential for CO_2 sequestration from BECCS. Indeed, the specific carbon capture and sequestration process efficiency, as well as other life cycle emissions, including reduction of land carbon stock, significantly affect the CO_2 flux potential.

Forestry

The United States is the largest producer of industrial roundwood products in the world, accounting for 19 percent of the global total. Other countries, particularly in the tropics, use most of harvested roundwood for heating and fuel consumed by households (FAO, 2015a). The large base of industrial timber production in the United States drives fuelwood use, which is mostly associated with timber harvesting for other products such as paper and lumber. The main resource categories are logging residues, increased whole-tree harvest of green or damaged timber, and other wood wastes, which includes unused mill and urban wood residues (Perlack et al., 2005).

Currently, the United States uses about 132 Mt annually of wood and wood waste for thermal and electric power and has the potential to nearly double this amount at a dry biomass price of 66 $/t based on economic modeling that excludes potential additional supplies from lands more than a 0.8 km (0.5 mi) from a road, protected areas, and steep slopes (DOE, 2016). With the exception of whole-tree harvest, potential additional wood for bioenergy is associated with improving utilization of timber and residues associated with current levels of timber harvest for other products; therefore, coupled with supply-area restrictions, there would be limited consequences for other forest values. Increasing whole-tree harvest is restricted by the amount of wood growth that exceeds current harvest, so that the potential increase is sustainable as long as growth is not impacted by factors such as increasing natural disturbances and climate change. However, the area that is harvested is highly variable among the scenarios modeled, indicating that there are potential impacts on net greenhouse gas emissions and other values of impacted forests over time.

Globally, 1,194 Mt/y wood biomass are used for fuel, mostly for household fuel and charcoal, approximately equal to the amount of industrial wood produced annually (FAO, 2016). The potential additional supply of wood for industrial biofuel at the global scale is not well known but could range from 1,316 to 10,532 Mt/y dry biomass (FAO, 2016).

The significant differences between current U.S. and global fuelwood use infrastructure may necessitate different strategies for large-scale deployment of BECCS. In the United States, much of the fuelwood is used to produce paper and other wood products at manufacturing facilities that are concentrated mainly in the south (DOE, 2016). In contrast, the global use of fuelwood is more dispersed, particularly in tropical areas where large wood processing facilities are mostly absent.

Organic Waste

Biogenically derived organic wastes and CO_2 fluxes potentials were estimated from three waste streams: (1) municipal solid waste, (2) construction and demolition, and (3) sewage and wastewater.

Municipal Solid Waste. The U.S. Environmental Protection Agency (EPA) estimated that the United States generated 230.5 Mt dry municipal solid waste in 2013 (4.4 lb/d per person), of which 70.3 percent was biogenic (paper 27.0 percent, food 14.6 percent, yard waste 13.5 percent, wood 6.2 percent, and leather, textiles, and rubber 9.0 percent) (EPA, 2016c). Based on these data and U.S. Census Bureau population estimates (Colby and Ortman, 2015), the dry biomass from municipal solid waste is estimated to be 167 Mt in 2017 and 199 Mt in 2040 (Table 4.5). From this, annual CO_2e flux potentials of 166 Mt in 2017 and 198 Mt in 2040 are estimated using a municipal solid waste CO_2 emissions per dry biomass factor of 0.82 t/t (EPA, 2014) (Table 4.5).

Construction and Demolition. EPA estimated that the United States generated 481 Mt of construction and demolition waste in 2013 (9.2 lb/d per person), of which 7.6 percent was biogenic (wood). Based on these data and U.S. Census Bureau population estimates (Colby and Ortman, 2015), the annual dry biomass from construction and demolition waste is estimated to be 37 Mt in 2017 and 44 Mt in 2040 (Table 4.5). From this, annual CO_2e flux potentials of 68 Mt in 2017 and 81 Mt in 2040 are estimated using a wood waste CO_2 emissions per dry biomass factor of 1.5 t/t (EPA, 2014).

Sewage and Wastewater. Seiple et al., 2017 estimated that the United States produces 12.56 Mt/y dry biomass of wastewater sludge, of which about 50 percent is beneficially used (6.23 Mt/y). Rose et al. (2015) reported a median human stool and urine dry solids generation rates of 29 g/d and 59 g/d, respectively, for a combined median dry biomass generation rate of 88 g/d per person. Based on this median generation rate and U.S. Census Bureau population estimates (Colby and Ortman, 2015) , the annual dry biomass from human sewage is estimated to be 10 Mt in 2017 and 12 Mt in 2040 (Table 4.5). Assuming dry human stool and urine have a carbon content of 20 percent and 13 percent by mass (Rose et al., 2015), respectively, then the annual CO_2e flux potentials from human sewage are estimated to be 6 Mt in 2017 and 7 Mt in 2040.

Carbon Capacity

According to the IEA (2016), most climate scenarios that keep average global temperature rise below 2°C include at least 14 Gt CO_2 cumulative removal from BECCS globally by 2050, or about 2 percent cumulative global emissions reduction. If the United

States committed to removing a proportional share of CO_2 emissions (15 percent of global emissions in 2015), then it would need to remove 2.1 Gt CO_2 by 2050.

Supply Capacity Basis

The U.S. lower-bound cumulative CO_2 storage capacity based on biomass supply achievable with minimal impacts on current land and biomass use is 6.0 Gt CO_2 by 2040, if annual CO_2 sequestration is ramped linearly from 0 percent to 100 percent of the lower-bound CO_2 flux potential (522 Mt/y CO_2) from 2018 to 2040. If continued at the same rate, the lower-bound cumulative CO_2 storage capacity is 11 Gt CO_2 by 2050. The U.S. upper-bound CO_2 storage capacity based on biomass supply achievable with minimal impacts on current land and biomass use is 17 Gt CO_2 by 2040, if annual CO_2 sequestration is ramped linearly from 0 percent to 100 percent of the upper-bound CO_2 flux potential (1,500 Mt/y CO_2) from 2018 to 2040. If continued at the same rate, the upper-bound cumulative CO_2 storage capacity is 32 Gt CO_2 by 2050.

The worldwide lower-bound CO_2 capacity is assessed by scaling the total global capacity by the same reduction factor utilized in the United States. A comparison of upper and lower bounds for total U.S. CO_2 capacity shows that lower-bound capacity is 35 percent of upper-bound capacity; thus, the global lower-bound CO_2 storage capacity is estimated to be 57-86 Gt CO_2 by 2050 if the annual CO_2 sequestration rate is increased linearly from 0 percent to 100 percent from 2018 to 2050. Based on the range of upper-bound global CO_2 flux potentials (10-15 Gt/y CO_2), the total global upper-bound cumulative CO_2 capacity is estimated to be 165-248 Gt CO_2 by 2050.

Sequestration Capacity Basis

One constraint on the carbon sequestration potential for biomass energy removal pathways is the availability and economic viability of carbon storage resources. For biomass combustion and fermentation pathways, the limitation is the availability and capacity of geological sequestration (see Chapter 7). For biomass thermochemical conversion to fuels with co-production of biochar, there are no apparent technical or economic limits to the amount of carbon that can be stored, regardless of how it is stored (i.e., as a soil amendment or in landfills).

Radiative Impacts

Creutzig et al. (2015) identified five main sources of radiative (life cycle) impacts for bioenergy systems: (1) GHG emissions from fossil fuels used along the value chain, (2) GHG emissions associated with biomass or biofuel combustion, (3) GHG emissions and uptakes from land disturbances, (4) emissions of short-lived climate forcers (e.g., black carbon) from biomass or biofuel combustion and of non-CO_2 GHGs (e.g., methane [CH_4], nitrous oxide [N_2O]) from land management, and (5) climate forcing resulting from alteration of the land surface (e.g., albedo changes).

A life cycle approach is essential to account for all GHG emissions and uptakes associated with BECCS technologies to determine their net contribution to climate change mitigation. Bioenergy with carbon capture and sequestration involves both fossil and biogenic carbon flows. Biogenic carbon flows consist of the uptake of CO_2 from the atmosphere by growing biomass during photosynthesis, and by CO_2 emissions from biological respiration, degradation, and combustion.

Fossil carbon flows consist of the CO_2 and CH_4 emissions from the combustion of the fossil fuels or materials needed by BECCS technologies. For example, transport of biomass by fossil fuel–powered vehicles or locomotives must be accounted for in estimating net carbon removal. Further, CO_2 is not the only GHG contributing to climate change, and CH_4 and nitrous oxide N_2O are especially relevant for biomass systems. For example, 75.1 percent of U.S. N_2O emissions in 2015 were attributed to agricultural soil management activities such as fertilizer application and other practices that increase nitrogen availability in the soil (EPA, 2017). Methane is also emitted during

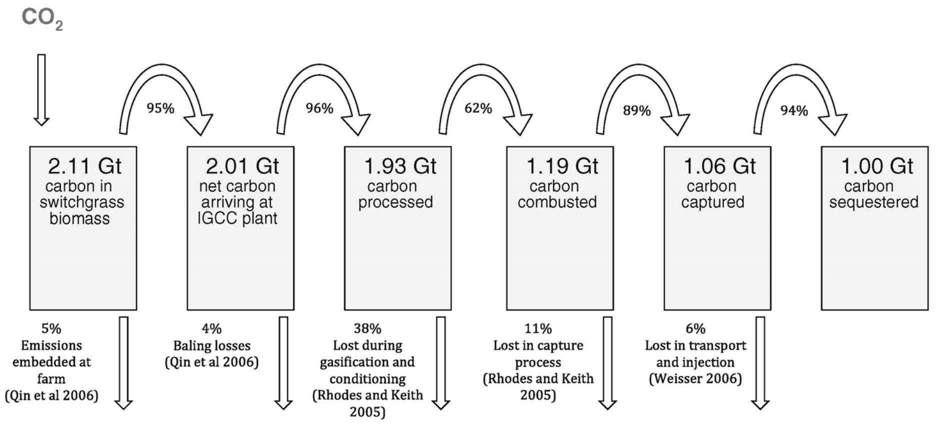

FIGURE 4.8 Carbon flows for switchgrass burned in an integrated gasification combined cycle facility retrofitted to burn biomass with carbon capture and sequestration.
SOURCE: Smith and Torn, 2013.

biological respiration, degradation, and combustion, and biomass decomposition in anaerobic conditions could lead to high CH_4 emissions. Other GHG emissions can also occur at different stages in the life cycle of a BECCS process. For example, natural gas can be used in biomass conversion processes, leading to CH_4 emissions. Figure 4.8 shows an example of "carbon losses" associated with BECCS for switchgrass burned in an integrated gasification combined cycle power plant with carbon capture and sequestration (data taken from the literature).

Fully accounting for net changes in carbon stocks and fluxes on land associated with bioenergy is an important element contributing to the net effect of BECCS on the atmosphere. The source of biomass, whether live vegetation or waste, determines the essential accounting elements. To calculate the effects on net CO_2 balance, it is first necessary to compare temporal bioenergy production scenarios with a projected business-as-usual baseline scenario to accurately reflect the incremental net change in emissions. The time horizon is important in several ways. Depending on the bioenergy source, it will take different times to recover the utilized biomass (sometimes called "re-paying carbon debt") and additional "time to carbon sequestration parity," which refers to the point at which the accumulated net (or "additional") GHG effect from using the bioenergy equals the net GHG effect of the baseline (often a "no-harvest" scenario) (Ter-Mikaelian et al., 2015). In sharp contrast to harvesting live trees, which may take decades or centuries to recover their original biomass and reach carbon sequestration parity, using wood residues for bioenergy that would otherwise have been left to decompose or slash-burned results in emissions reductions over a shorter term. However, if the wood residues would otherwise have been used in a long-lived product such as particle board, it could take decades for the use of this material for bioenergy to have a positive effect of reducing atmospheric CO_2. Indirect effects, such as broader impacts on land use and supply of other wood products, and their consequent impacts on GHG emissions are important to consider when calculating the overall net CO_2 balance.

Land-cover changes or land-use disturbances (e.g., forest harvesting or conversion of natural lands to crops) can also lead to changes in albedo (Betts and Ball, 1997; Zhao and Jackson, 2014), surface roughness, and evapotranspiration (Swann et al., 2010), influencing the climate system. Albedo changes are the dominant effect, especially in areas with seasonal snow cover (Bathiany et al., 2010), and can possibly be stronger than those of associated biomass carbon sequestration (Bernier et al., 2011; Betts, 2000; Jones et al., 2013b; O'Halloran et al., 2012). Although very important, it is difficult to quantify these biogeophysical climate impacts at large scale because they are site specific and vary in magnitude across geographic regions (Anderson-Teixeira et al., 2012).

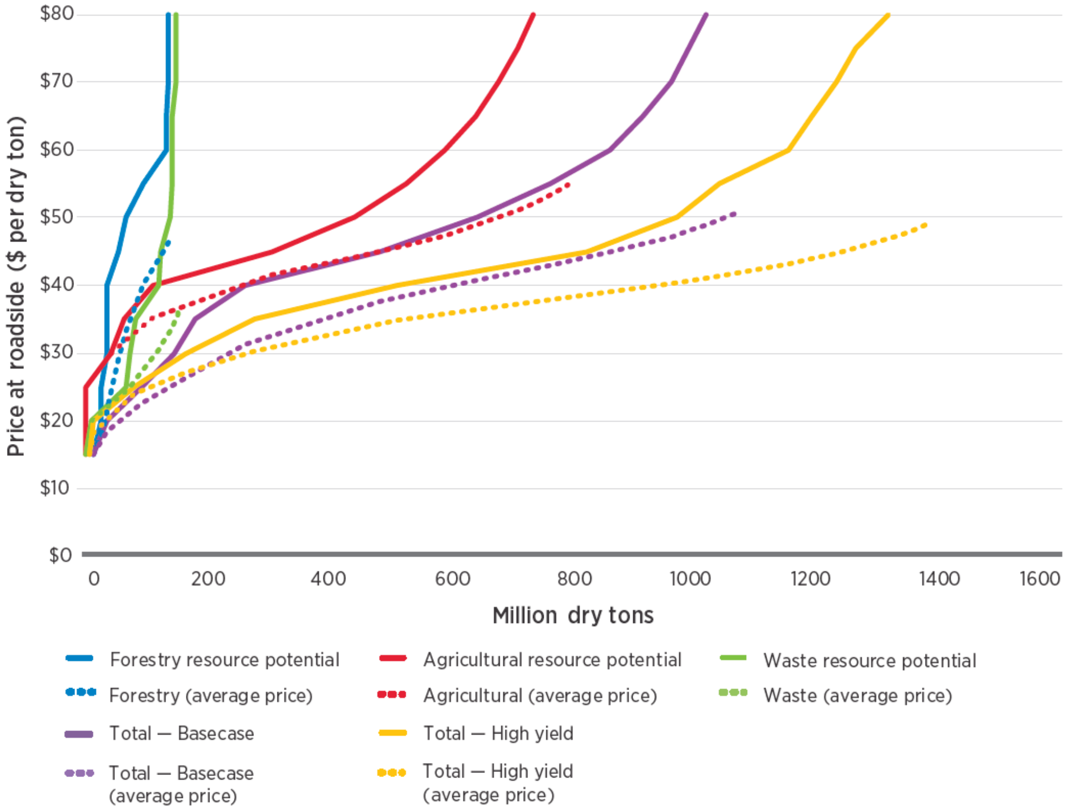

FIGURE 4.9 Potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average roadside dry biomass prices in 2040. SOURCE: DOE, 2016.

ESTIMATED COSTS OF IMPLEMENTING BECCS

The extent to which BECCS is implemented will largely depend on factors such as the costs of biomass supply of competing electricity generation approaches, such as natural gas. These costs are summarized below, followed by specific estimates of carbon costs for CO_2 generated and captured in a power plant and biochar produced by pyrolysis.

Biomass Supply Costs

Cost per ton of biomass supply is affected by many factors: productivity or yields per hectare, transportation (distance from roadside), fertilizer additions, processing, stumpage price or payment to grower, harvest cost, and other feedstock specific

TABLE 4.6 Estimated Levelized Cost of Electricity

Power Plant Type	Capacity Factor	Levelized Cost of Electricity ($\$2016/MWh_e$)				
		Capital Cost	Fixed O&M	Variable O&M	Transmission Investment	Total
Natural Gas	87%	14.0	1.4	42.0	1.1	58.6
Biomass	83%	47.2	15.2	34.2	1.2	97.7

NOTE: Based on weighted average of regional values for projected capacity additions from new U.S. power plants entering service in 2022. O&M = operations and maintenance. SOURCE: EIA, 2017b.

factors (DOE, 2011). Figure 4.9 shows the rise in prices for each category of feedstock as the total supply increases, and the relative availability of different feedstocks at different supply levels.

Electricity Costs

CO_2 capture, compression, and transportation to a site for geological sequestration is considered primarily for generating thermal and electrical power through biomass-fueled combustion, as opposed to producing fuels. The primary challenge for biomass electrical power with carbon capture and sequestration is the low efficiency (typically less than 25 percent) of biomass power plants. Low biomass power plant efficiency increases the already high cost of feedstocks ($50-80/t or $3-4/GJ dry biomass) and capital (more than $4,100/kW electricity), which ultimately yields an uncompetitive LCOE of about $100/MWh ($28/GJ) (see Table 4.6) (EIA, 2017b). By contrast, conventional natural gas combined cycle power plants have high efficiency (typically greater than 45 percent), low fuel costs ($2-3/GJ or $2-3/Mcf natural gas), low capital costs (less than $920/kW electricity), which yields an LCOE of about $60/MWh ($17/GJ)—nearly half the cost of biomass electrical power. Therefore, research and development (R&D) in this area should prioritize increasing biomass power plant efficiency over R&D for carbon capture, compression, and transportation research.

Biomass-to-Power with Carbon Capture

Two factors influence the economics of biomass-power generation with carbon capture: the LCOE and the cost of carbon capture. Based on data from the Federal Energy Regulatory Commission (FERC, 2016), the EIA estimated that the LCOE in 2016 for an average coal power plant was \$36.1/MWh—\$5.1/MWh operations, \$5.5/MWh maintenance, and \$25.5/MWh fuel costs. Assuming operations and maintenance (O&M) costs do not substantially differ between coal and biomass power plants, the cost of biomass-derived electricity can be estimated by modifying the current cost of fossil fuel–derived electricity to consider biomass feedstock and carbon capture costs. For a simple and direct comparison of fuels, the efficiencies of biomass and coal power plant are assumed to be the same, even though they are largely dependent on firing percentage and biomass pretreatment, such as torrefaction or densification. According to the U.S. EIA (2017a), the average coal power plant efficiency was 32.5 percent in 2016. Assuming a higher heating value for biomass of 17 GJ/t (about half that of coal) and a farmgate cost of \$66/t, the farmgate biomass cost contribution to biomass LCOE is \$43/MWh—almost 70 percent higher than coal. Biomass transportation contributes another \$14/MWh to biomass electricity costs, assuming that transportation costs equal those for coal at \$22/t (EIA, 2017a). Combining biomass farmgate and transportation costs, the total fuel contribution power plant electricity cost is \$57/MWh—more than twice the \$26/MWh for coal. Because fuel costs dominate the LCOE, substituting biomass for coal has a significant impact on electricity costs, as evidenced by the increase in the LCOE from \$36/MWh for coal to \$67/MWh for biomass.

Inclusion of CO_2 capture increases the plant costs. Based on an estimated post-combustion carbon capture cost of \$46/tCO_2 (Rubin et al., 2015), carbon capture adds \$52/MWh to electricity generation costs. Thus, the LCOE for biomass power with carbon capture is about \$119/MWh. Assuming a carbon content of 47.5 percent by mass across all biomass types, the total cost to generate electricity with carbon capture at a biomass power plant is \$105/tCO_2, compared to the total cost to generate electricity without carbon capture at a baseline coal power plant of about \$70/tCO_2.

Biomass-to-Fuel with Biochar Carbon Sequestration

Currently, most thermochemical approaches to convert biomass to fuel are optimized for maximum fuel production, where the co-produced biochar is burned to provide process heat. If we assume that the biochar is instead used as a soil amendment to sequester carbon in the soil (or simply buried) and this process heat was instead provided by natural gas at a price of \$2-7/GJ (\$2-7/Mcf), by proxy the effective biochar carbon capture cost would be about \$37-132/t CO_2. Because biochar is easily separated and, if stored locally, suffers little oxidation to CO_2, the cost to "avoid" CO_2 will be nearly the same as that to "capture" CO_2. This estimate does not assume a cost offset from the sale of biochar to agriculture users because the biochar market is currently small relative to the scale necessary to provide climate benefits. Recently, the USDA commissioned a survey of the U.S. biochar industry and estimated the current biochar market range from 35,000 to 70,000 t/y—roughly equivalent to sequestering 75,000 to 150,000 t/y CO_2e (USDA, 2018). Reported biochar sales prices ranged widely from a low of \$600/t and an average price of \$1,030/t. Assuming a carbon content of 70 percent by weight, these prices correspond to a carbon price of \$230-400/t CO_2e.

SECONDARY IMPACTS

The IPCC has paid little attention to nonclimate impacts on ecosystems and biodiversity from large-scale CO_2 removal technologies such as BECCS (Williamson, 2016). However, several publications in recent years have addressed a set of different types of environmental and societal impacts associated with bioenergy and BECCS. Aside from physical constraints on biomass production, life cycle GHG emissions, and other potential radiative impacts, there are key uncertainties regarding indirect emissions, adverse effects on food security, impacts on biodiversity and land conservation, competition for water resources, and social equity and acceptance issues (Sanchez and Kammen, 2016).

Environmental Impacts

The area of land required per unit mass of carbon removed from the atmosphere is particularly important for BECCS, leading to different potential impacts regarding land-use change, land conservation (e.g., nutrient availability), and biodiversity. Some researchers have provided evidence that suggests some types of BECCS are incompatible with human development within safe operating margins, because they begin to threaten planetary boundaries, such as biosphere integrity and nitrogen flows (Heck et al., 2018). As described above, both U.S. and global lower-bound estimates for BECCS would not require land-use changes because biomass would be sourced from waste and residues from existing land uses. The U.S. upper-bound estimate of 1.5 Gt/y CO_2, based on an average productivity of 18 t/ha CO_2e (Table 4.2) indicates a land area requirement of about 78 Mha. For the global upper-bound estimate of 10-15 Gt/y CO_2, Smith et al. (2016) estimated that the land area required to deliver just 12 Gt/y CO_2e is about 380-700 Mha for all sources, including wastes and residues from existing land uses, and dedicated energy crops such as willow and poplar or miscanthus on a range of productivity classes. This land area represents 36 percent to 163 percent of land identified as abandoned or marginal[3] (Canadell and Schulze, 2014). Similarly, Humpenöder et al. (2014) found the land requirements to range from 300-500 Mha, depending on whether afforestation was also a major part of a carbon dioxide removal program.

Carbon removal through afforestation and reforestation also requires large areas of land (~2,800 Mha), potentially an order of magnitude greater than that required for BECCS (see Figure 3.3) (Humpenöder et al., 2014). This figure shows the simulated time series of global land use for BECCS and forestry NETs. Therefore, large-scale implementation of BECCS will compete with afforestation/reforestation, as well as with food production and delivery of other ecosystem services (e.g. Bustamante et al., 2014).

Nutrient removal associated with biomass harvesting (for energy crops as well as collecting agricultural and forest residues instead of leaving them on the ground as nutrients) differs several-fold among biomass sources. Such nutrient removal prevents further emissions due to decomposition of the biomass, but it could lead to nutrient depletion depending on the vegetation or the land use replaced (Smith et al., 2016). Moreover, enhanced cropping will increase nutrient runoff to the sea and thereby eutrophication, which could lead to reduced coastal fisheries yields and potential negative impacts on coastal blue carbon. The use of bioenergy feedstock with low nutrient concentrations such as residues, forest, and lignocellulosic biomass could help to mitigate nutrient depletion and runoff.

Bioenergy feedstock from food and fiber production waste does not have a direct effect on existing land use. However, establishing new dedicated bioenergy feedstock production capacity will initiate direct competition with other land uses, unless the land is marginally productive and not actively managed. These direct and indirect effects should be considered in the overall accounting for net effects on CO_2, and if significant, can be quantified using an integrated economic land-use modeling approach (Plevin et al., 2010; Searchinger et al., 2008). There may also be effects on commodity supplies and prices for goods that may use the same material, for example, wood products (Ahlgren et al., 2013). Changes in production of other goods may in turn affect CO_2 balance because of differences in production systems and use and disposal patterns of biomass products, and potentially other materials that can be substituted for biomass products. Moreover, the modeling approach selected to predict these

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[3] Estimates of marginal land are uncertain due to inconsistencies in the definition of marginal. See Chapter 3 for a detailed discussion of marginal land.

indirect effects should consider the entire world because of globalized food and material markets.

Unirrigated bioenergy crops cause evaporative losses that are higher than that of average short vegetation (Smith et al., 2016). The higher yields of irrigated bioenergy crops can reduce the pressure on land but can increase the pressure on freshwater ecosystems and competition with other users, leading to a trade-off between land and water requirements (Bonsch et al., 2016). Important water withdrawal for energy crops irrigation could lead to freshwater ecosystem degradation and aquatic biodiversity loss. Moreover, the CCS process also requires the use of water. Smith et al. (2016) estimate the amount of water required to deliver 12 Gt/y CO_2e sequestration through BECCS to be approximately 3 percent of the total amount of water currently used by human activities. However, water can also be extracted from CO_2 storage operations so that water use associated with the carbon capture and storage process is case-specific.

In an effort to guide policymaking, researchers are increasingly using IAMs to develop potential mitigation scenarios for different emission pathways. These prospective models integrate representations of human systems (e.g., techno-economic models) and physical processes associated with climate change and/or other environmental impacts (e.g., carbon cycle, water availability). Despite their limitations, IAMs can enhance understanding of how possible technological or policy choices might lead to different outcomes (Edenhofer et al., 2014). Because they capture linkages between regions through trade in energy and agricultural goods, among others, they are suitable for identifying potential indirect impacts from BECCS. However, improvements are still needed to include impacts on biodiversity, ecosystem services, and water resources.

Societal Impacts

Energy crops compete with food crops for available agricultural land. Therefore, the use of BECCS might lead to food security issues. For instance, Powell and Lenton (2012) show that the climate mitigation potential of BECCS highly depends on assumptions regarding future food production efficiency and proportion of meat in diets; the most pessimistic scenarios (low efficiency and high meat proportion) lead to more warming. This competition for land leads to increased food prices. Because food prices are very inelastic, they must rise to ensure that enough land is allocated to food production in high mitigation scenarios (Calvin et al., 2014). Such increase in food prices was observed several years ago. Some authors identify the increase in first-generation biofuel production as the main cause (Tangermann, 2008; World Bank, 2008). Zhang et al. (2010) also link increased ethanol production to short-run agricultural commodity prices. Crude oil prices and droughts might also influence food prices in the short term (Ajanovic, 2011). Higher food prices reduce low-income populations' access to food, especially in developing countries, potentially leading to malnourishment and social discord (Rosegrant, 2008).

RESEARCH AGENDA

Scientific and Technical Questions

In developing its research agenda for BECCS, the committee was guided by the following questions:

- What are the limits to biomass resource potential as a carbon negative approach when considering secondary impacts such as food security, competition for water and land use, albedo changes, and biodiversity?
- Can a sufficiently diverse biomass feedstock supply chain be developed to allow for the conversion of existing coal-fired power plants to biomass (1 GW-scale)?
- Is it worth investing in biomass-to-power considering that it would take more than 1Gt dry biomass (~ 15 EJ primary energy) to replace coal in the United States (~ 17 EJ primary energy) alone?
- How does biochar soil amendment affect agricultural productivity, water use, and albedo? And, what is the carbon sequestration limit, if any, for biochar soil amendment?
- What are the techno-economic implications of optimizing current biomass-to-fuel processes for net carbon removal?

Definitions

The proposed BECCS research agenda uses definitions adapted from DOE's Clean Coal Program (DOE, 2015a) for *technology readiness levels* (*TRLs*), *bench-scale*, *pilot-scale*, and *demonstration-scale*, provided in Table 4.7. These definitions assume commercial-scale biomass-to-power or fuel plants have a dry biomass capacity of about 1,000 t/d, roughly equivalent to a fuel heating value of 220 MW at 19 GJ/t dry biomass.

TABLE 4.7 Bioenergy with Carbon Capture and Storage (BECCS) Technology Readiness Levels and Descriptions Based on U.S. Department of Energy Definitions

	TRL	DOE Definition	BECCS Description
Applied Research	1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples include paper studies of a technology's basic properties.
	2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
	3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology (e.g., individual technology components have undergone laboratory-scale testing).
Development	4	Component and/or system validation in a laboratory environment	A bench-scale component and/or system has been developed and validated in the laboratory environment. Bench-scale prototype is defined as less than 1 percent of final scale (e.g., technology has undergone bench-scale testing with biomass feed stock/simulated feedstock of 0.1-1.0 t/d)
	5	Laboratory-scale similar-system validation in a relevant environment	The basic technological components are integrated so that the bench-scale system configuration is similar to the final application in almost all respects. Bench-scale prototype is defined as less than 1 percent of final scale (e.g., complete technology has undergone bench-scale testing using actual dry biomass feed stock of 0.01-1.0 t/d).
	6	Engineering/pilot-scale prototypical system demonstrated in a relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. Pilot-scale prototype is defined as being 1-5 percent final scale (e.g., complete technology has undergone small pilot-scale testing using actual dry biomass at a scale of approximately 10-50 t/d).

TABLE 4.7 Continued

	TRL	DOE Definition	BECCS Description
Demonstration	7	System prototype demonstrated in a plant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete. Demonstration-scale prototype is defined as 5-25 percent of final scale or design and development of a 50-250 t/d dry biomass plant (e.g., complete technology has undergone large pilot-scale testing using dry biomass feedstock at a scale equivalent to approximately 50-250 t/d).
	8	Actual system completed and qualified through test and demonstration in a plant environment	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include startup, testing, and evaluation of the system within a 50-250 t/d dry biomass capacity plant (e.g., complete and fully integrated technology has been initiated at full-scale demonstration including startup, testing, and evaluation of using dry biomass feedstock at a scale equivalent to approximately 50 t/d dry or greater).
	9	Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions. The scale of this technology is expected to be 50-250 t/d dry biomass capacity plant (e.g., complete and fully integrated technology has undergone full-scale demonstration testing using dry biomass feedstock at a scale equivalent to approximately 50 t/d dry biomass or greater).

NOTES: DOE, U.S. Department of Energy; R&D, research and development; TRL, technology readiness level.
SOURCE: Adapted from DOE, 2015a.

Components and Tasks

The committee's research agenda to advance BECCS technology has four main components: (1) crosscutting activities, (2) biomass-to-power with carbon capture, (3) biomass-to-fuel with biochar, and (4) biomass-to-fuel with carbon capture. These research components, specific tasks, and estimated budget are summarized in Table 4.8 and described in detail below.

TABLE 4.8 Bioenergy with Carbon Capture Research Agenda, Budget, and Budget Justification

Components and Tasks	TRL	Budget ($M/y)	Duration (y)	Budget Justification
1. Crosscutting Activities				
1.1 Regional Life Cycle Assessments and Integrated Assessment Modeling				
Model Development	1-3	1.5-5.0	10	$0.5-1.0MM per project, 3-5 projects/y, 1-3 y projects
Secondary Impacts	1-3	0.6-2.5	10	$0.5-1.0MM per project, 2-3 projects/y, 1-3 y projects
Spatial and Temporal Resolution	1-3	0.6-2.5	10	$0.5-1.0MM per project, 2-3 projects/y, 1-3 y projects
Food Security Impacts	1-3	0.5-2.0	10	$0.5-1.0MM per project, 2-3 projects/y, 1-3 y projects
Technology Assessments	1-3	0.5-2.0	10	$0.5-1.0MM per project, 2-3 projects/y, 1-3 y projects
2. Biomass-to-Power with Carbon Capture				
2.1 Biomass Supply and Logistics				
Pretreatment Technology	1-3	1.2-3.5	5	$0.2-0.5MM per project, 6-7 projects/y, 1-2 y projects
Feedstock Logistics Research	1-3	0.8-2.5	5	$0.2-0.5MM per project, 4-5 projects/y, 1-2 y projects
Bench-Scale Prototypes	4-5	2.0-5.0	5	$0.5-1.0MM per project, bench-scale <1 t/d biomass, 4-5 projects/y, 1-2 y projects
Feasibility Study (Stage-Gate)	5-6	0.2-0.3	5	Rule-of-thumb: 1% est. plant capex (100 t/d ~ $5MM), $0.05MM each, 4-5 studies/y
Pilot-Scale Prototypes	6	6.0-12	5	$2-3MM per project, pilot-scale ~ 10 t/d biomass, 3-4 projects/y, 1-2 y projects

TABLE 4.8 Continued

Components and Tasks	TRL	Budget ($M/y)	Duration (y)	Budget Justification
Pilot Testing Facility	6	2.0-2.5	5	$500K/FTE, 4-5 FTE per facility, 1 facility, 5 y operation
Engineering Study (Stage-Gate)	6-7	3.7-8.8	1	2% of depot-level demo project, at 1,000-2,000 t/d, $100-120/t, 5 y, $180-440MM per project
Depot-Level Demonstration	7-9	37-88	5	Budget to be revised from engineering study, $180-440MM per project, 5-y projects
2.2 High Efficiency Biomass Power				
Efficient Biomass Power Concepts	1-3	1.0-7.0	10	$0.2-1.0MM per project, 5-7 projects/y, 1-3 y project
Bench-Scale Prototypes	4-5	3.0-10	10	$1-2MM per project, <1 t/d biomass, 3-5 projects/y, 1-3 y projects
Feasibility Study (Stage-Gate)	5-6	1.0-3.0	10	Rule-of-thumb: 1% est. plant capex ($100MM), $1MM each, 1-3 studies, 1-3 y projects
Pilot-Scale Prototypes	6	10-15	7	$5-7MM per pilot-scale plant, ~10 t/d biomass, 2-3 projects/y, 1-3 y projects
Pilot Testing Facility	6	2.0-2.5	7	$500K/FTE, 4-5 FTE per facility, 1 facility
Engineering Study (Stage-Gate)	6-7	2.0-6.0	5	Rule-of-thumb: 2% est. plant capex ($100MM), $2MM each, 1-3 studies
Demonstration-Scale Prototypes	7-9	20-50	5	$20-25MM per demo-scale plant, ~100 t/d biomass, 1-2 projects/y, 1-3 y projects

continued

TABLE 4.8 Continued

Components and Tasks	TRL	Budget ($M/y)	Duration (y)	Budget Justification
3. Biomass-to-Fuel with Biochar				
Biochar Soil Amendments	1-3	0.4-3.0	10	$0.2-1.0MM per project, 2-3 projects/y, 1-3 y projects
Carbon Negative Pathways	1-3	1.0-7.0	10	$0.2-1.0MM per project, 5-7 projects/y, 1-3 y projects
Bench-Scale Prototypes	4-5	3.0-10	10	$1-2MM per project, <1 t/d biomass, 3-5 projects/y, 1-3 y projects
Feasibility Study (Stage-Gate)	5-6	1.0-3.0	10	Rule-of-thumb: 1% est. plant capex ($100MM), $1MM each, 1-3 studies, 1-3 y projects
Pilot-Scale Prototypes	6	10-21	10	$5-7MM per pilot-scale plant, ~10 t/d biomass, 2-3 projects/y, 1-3 y projects
Pilot Testing Facility	6	2.0-2.5	10	$500K/FTE, 4-5 FTE per facility, 1 facility, 10-y operation
Engineering Study (Stage-Gate)	6-7	2.0-6.0	5	Rule-of-thumb: 2% est. plant capex ($100MM), $2MM each, 1-3 studies
Demonstration-Scale Prototypes	7-9	20-50	10	$20-25MM per demo-scale plant, ~100 t/d biomass, 1-2 projects a year, 1-3 y projects
4. Biomass-to-Fuel with Carbon Capture				
Carbon Negative Pathways	1-3	4.2-6.0	10	$0.2-1.0MM per project, 7-10 projects/y, 1-3 y projects

Component 1. Crosscutting Activities

Task 1.1 Regional Life Cycle Assessments and Integrated Assessment Modeling

The LCA methodology is a mature tool to determine the climate change mitigation potential of BECCS approaches in different contexts. It can therefore be used to estimate the total amount of CO_2 that could be removed from the atmosphere using BECCS in the United States. However, GHG emissions associated with indirect land-use change and other potential indirect effects from competition between uses for biomass and land may occur. IAMs allow for the consideration of these indirect greenhouse gas emissions, because they combine economic and physical models within a coupled framework. However, improvements are still needed. Reducing uncertainty in the outcomes is crucial to increase the robustness of the models that are used as inputs (Popp et al., 2014). More sensitivity analyses should be performed to understand better the implications of various parameters and assumptions. Other carbon dioxide removal approaches such as direct air capture, biochar, or soil carbon sequestration should be incorporated to the models to account for the full portfolio of potential solutions and to improve our understanding of how BECCS and other land use–based mitigation interact in different economic and political contexts (Popp et al., 2014). Most IAMs also exclude important elements such as impacts on ecosystem services, water resources, and biodiversity. Indeed, increasing bioenergy production is likely to lead to losses in ecosystem services and biodiversity, radiative impacts from albedo changes, and water resources depletion (Calvin et al., 2014). There is a need to better represent these secondary impacts in IAMs. Finer scale modeling may be required to project the effects of more local parameters. IAMs should also be updated to reflect the most recent understanding of the responses of consumers to demand-side incentives to reduce meat consumption and waste (Clark and Tilman, 2017; Griscom et al., 2017; Poore and Nemecek, 2018; Stehfest et al., 2009). The committee recognizes the need for additional social sciences research on reducing meat consumption and food waste, but substantial work on these topics, motivated health and economics concerns, is already occurring . Finally, the field requires a better understanding of social consequences, such as the effect of food price increases on food security.

Academic researchers and national laboratories should conduct this research program, because of the large-scale, integrated analyses required and the relevant work that is ongoing in these institutions. National laboratories should be engaged to develop and curate publicly accessible IAM platforms that can be leveraged by academic researchers and to coordinate international IAM efforts. This program would fall within existing research portfolios at USDA, DOE, and EPA. A coordinated, cross-agency effort to develop IAMs is recommended.

Model Development

The objective of this activity is to improve the robustness of IAMs, including for other carbon dioxide removal approaches, and to develop better estimates of critical parameters. Competition among different land uses will likely increase as global population increases, as well as demand for food, fiber, and other ecosystem services such as biodiversity. Of particular concern for BECCS deployment will be competition for the land needed to produce biomass for bioenergy and the same land needed for other carbon dioxide removal approaches such as afforestation. IAMs are well suited for analyzing how land-use decisions at an aggregate scale are influenced by prices for different commodities as well as policies that affect food, fiber, and bioenergy production; however, some of these demand-driven price factors may not be well represented in current models. Research is needed to improve the estimation of critical parameters such as biomass yields in IAMs and to include other carbon dioxide removal approaches to develop future scenarios that account for the full portfolio of potential climate mitigation techniques.

Secondary Impacts

The field requires improved IAMs of the impact of bioenergy technology deployment on ecosystem services, biodiversity, albedo changes, and water resources. Large-scale bioenergy production might result in negative effects on nonclimate sustainability issues. A multicriteria analysis has shown potential trade-offs between different sustainability issues and possible mitigation solutions (Humpenöder et al., 2018). However, research is still needed to better estimate and quantify these potential environmental impacts. For instance, water availability for energy crops remains a research area of interest. Improved geo-hydrological models and analysis at the regional level are needed to better understand constraints and potential solutions regarding impacts on water (Slade et al., 2014).

Academic researchers and national laboratories should perform this research, which is ongoing in universities and would benefit from additional support to fill knowledge gaps.

Spatial and Temporal Resolution

The objective of this activity is to create IAMs with higher spatial and temporal resolution. Most IAMs function at a global scale and therefore may not accurately represent actual conditions and system responses at the smaller scales needed for effective policy- and decision-making. As a result, researchers should explore ways to nest or link smaller-scale models within global-scale models (similar to what has been done with global climate models) that can be tailored to more local circumstances, but still function adequately within the global context.

Food Security Impacts

The objective of this activity is to improve understanding of the impact of BECCS technology deployment on food prices and food security. The large-scale implementation of land-based carbon dioxide removal approaches might lead to food price increases through competition for land, as has been shown in some studies (Kreidenweis et al., 2016; Smith et al., 2013). However, if the extra land needed is already available or if biomass feedstock does not compete with agricultural land, food price increases may not be that high (Lotze-Campen et al., 2014), and mitigation measures can be implemented to limit impacts on food security (Smith et al., 2013). IAMs estimate food price increases caused by large-scale bioenergy production. However, the potential impacts on food security issues (e.g., malnutrition, food riots) are not yet well understood. Research is needed to better understand these impacts and to develop policy guidelines for the implementation of potential mitigation measures. Research is also needed to design appropriate safeguards to ensure food security. A good deal of social science and policy-focused research has already been conducted on the general safeguards required to ensure food security in the face of large-scale land-use change. This work needs to be reinterpreted and revised for the special case of BECCS.

Technology Assessments

Few LCA studies have assessed the potential environmental impacts associated with carbon dioxide removal technologies. LCA methodology relies heavily on available data, models, and assumptions to quantify CO_2 life cycle emissions. It is therefore critical to follow similar methodological rules when comparing LCA results to ensure valid conclusions. Product category rules allow consistency and comparability of results by providing product- or sector-specific guidance. There is a need to develop such consensual LCA guidelines specific to biomass energy carbon dioxide removal technologies in the United States.

Component 2. Biomass-to-Power with Carbon Capture

The research agenda for biomass-to-power with carbon capture has two main elements: (1) biomass pretreatment and logistics for the conversion of conventional pulverized coal power plants to biomass and (2) high-efficiency biomass power generation. Pretreated biomass feedstocks for operation in conventional coal plants will, in the near-term, leverage worldwide fixed-capital coal power plant investments, while creating a biomass fuel supply infrastructure to support more efficient biomass power generation. In the long-term, high-efficiency biomass power generation will be essential to the sustainability, scalability, and cost-effectiveness of carbon negative biomass-to-power.

Task 2.1 Biomass Supply and Logistics

The development of a robust biomass feedstock supply and effective supply chain is a key to replacing today's coal power plants with biomass power plants. This research task aims to establish a coal-compatible biomass feedstock depot capable of delivering enough fuel to completely convert a coal power plant to biomass. The program has two main thrusts: (1) pretreatment technology for converting biomass into a drop-in replacement for coal and (2) logistics research to address biomass supply chain issues (i.e., production, storage, handling, and transportation).

This research program will need to leverage the nation's entire innovation ecosystem, from academia to private industry. Both the agricultural and electric power industries should be engaged early in this program. Applied research and bench-scale prototype development of pretreatment technology and supply logistics should be performed by university researchers, national laboratories, and R&D organizations. Pilot and demonstration-scale development should leverage public-private partnerships, with private industry and start-up companies taking the lead with support from the national laboratories. In particular, national laboratories should be engaged to operate pilot-scale testing facilities. Program managers should contract third-party engineering design and estimation firms to provide engineering and economic assessments of technologies under consideration for scale-up (stage-gate). The management and operation of the final biomass demonstration depot project should be a public-private partnership, preferably hosted by a large utility with coal power generation assets.

This program would align with the research portfolios and funding priorities of DOE and USDA, and its projects could be governed according to these agencies' guidelines.

Pretreatment Technology

The objective of this activity is to identify optimal biomass densification, pretreatment, and formation techniques that convert a variety of biomass feedstocks into a standardized drop-in replace for coal. Research is needed to evaluate and develop biomass densification, pretreatment, and formation techniques using a variety of biomass feedstocks (agricultural byproducts, energy crops, wood, and organic waste) into a product that is compatible with coal-fired power plants. Promising technologies should be promoted from applied research to bench-scale prototypes (< 1 t/d biomass) and pilot-scale prototypes (10 t/d biomass). Process designs should be aimed at modualarized solutions with dry biomass capacity of about 100 t/d to enable a distributed pretreated biomass supply chain.

Feedstock Logistics Research

The objective of this activity is to determine the supply chain logistics (i.e., sources, collection, processing, storage, and transporation) needed to deliver pretreated biomass fuel to U.S. coal power plants with the aim of creating a national pretreated biomass demonstration depot capable of supplying enough biomass to convert a conventional coal power plant to biomass. Research projects should evaluate the logistics required to supply an existing U.S. coal power plant less than 20 years old with pretreated biomass.

The proposed research is distinct from the current feedstock supply and logistics research at DOE (BETO, 2017), in that its objective is to pretreat biomass at or near production, that is, *distributed biomass pretreatment*. This research should consider the availability of geological CO_2 sequestration for implementing biomass-to-power with CCS. Finally, this research should cover biomass production, waste resources, collection, processing, and transportation and carbon LCAs, supply chain economics, and barriers to implementation.

Task 2.2 High Efficiency Biomass Power

The fundamental challenge for biomass-to-power conversion efficiency is the relatively low fire-side boiler temperature in a conventional biomass power plant, which is typically well below 700°C. At these temperatures, the technology options for thermal-to-electric conversion are limited to conventional steam turbines (Rankine cycle) with efficiencies below 40 percent. Thus, research is needed to develop technology that converts biomass-to-heat and produces working fluid temperatures over 1,100°C and/or biomass-to-power with conversion efficiencies over 60 percent. Some possible, but not exhaustive, transformational research directions include (1) liquid phase (molten glass or salt) combustion; (2) chemical looping combustion; (3) novel reactor designs that are process intensified and leverage additive manufacturing; (4) new high-temperature, corrosion-resistant materials and materials processing; (5) high-efficiency heat exchanger designs that are process intensified and leverage additive manufacturing; (6) gasification pathways; (7) liquification and liquid combustion pathways; (8) in situ high-temperature gas clean-up; (9) biomass pretreatment processes; and (10) small-scale, modular power generation concepts.

This research program will need to leverage the nation's entire innovation ecosystem, from academia to private industry. Applied research and bench-scale prototype development of high efficiency biomass-to-power concepts should be conducted by university researchers, national laboratories, and R&D organizations. Pilot and demonstration-scale development should be led by private industry and start-up companies with support from universities, national laboratories, and R&D organizations. In particular, national laboratories should be engaged to operate pilot-scale testing facilities. Program managers should contract third-party engineering design and estimation firms to provide engineering and economic assessments of technologies under consideration for scale-up (stage-gates). This program would fit within the research portfolios and funding priorities of DOE. The DOE Office of Fossil Energy's National Energy Technology Laboratory (NETL) has the most relevant expertise and experience for managing this program because of its long history of developing coal power plant technology, advance power generation, and carbon capture technology—even though biomass power does not exactly fall within the priorities of Fossil Energy.

Component 3. Biomass-to-Fuel with Biochar

Biomass-to-fuel with biochar processes hold tremendous promise as a cost-effective, carbon negative pathway. Despite some recent high-profile failures to commercialize thermochemical biomass-to-fuels technology (Fehrenbacher, 2015), promising new biomass-to-fuel processes continue to emerge. For example, a recent techno-economic analysis of a fast pyrolysis with hydrotreating process suggests this technology can make a gasoline/diesel blendstock with a minimum fuel selling price of $29/GJ ($3.46/gge) from $88/t dry wood and with negative carbon emissions of

-3 kg/GJ CO_2 per fuel produced (NREL, 2015). Another example is a new integrated hydropyrolysis with hydrotreating process (IH^2) that makes drop-in gasoline and diesel fuels with a projected minimum fuel selling price of $14/GJ ($1.68/gge) from $79/t dry wood and negative carbon emissions of 0.89 kg/GJ CO_2 per fuel produced (Maleche et al., 2014; Tan et al., 2014). Although these technologies still have net positive life-cycle GHG emissions, the processes themselves can be carbon negative.

The carbon negative biomass-to-fuel with biochar processes can be advanced by determining the value of co-produced biochar and by optimizing existing processes or developing new pathways that maximize carbon removal. To this end, research in two main areas is proposed. First, biochar permanence in soil and impact on crop productivity needs better quantification to determine its long-term value as a soil amendment and viability for carbon sequestration. Second, carbon negative biomass-to-fuel conversion pathways need to be developed that are ideally both profitable from fuel production and carbon negative through the co-production of large quantities of sequestered biochar.

This research program will need to leverage the nation's entire innovation ecosystem, from academia to private industry. Applied research and bench-scale prototype development of carbon negative biomass-to-fuel processes and enabling subsystems should be conducted by university researchers, national laboratories, and R&D organizations. Pilot and demonstration-scale development should be led by private industry and start-up companies with support from universities, national laboratories, and R&D organizations. National laboratories should be engaged to operate pilot-scale testing facilities. Program managers should contract third-party engineering design and estimation firms to provide engineering and economic assessments of technologies under consideration for scale-up (stage-gates). This program would fit within the research portfolios and funding priorities of the DOE and USDA.

Biochar Soil Amendments

Quantitative assessments are needed of how biochar soil amendments affect agricultural productivity, water use, and albedo. In addition, the carbon sequestration limit and permanence of biochar as a soil amendment needs to be assessed to accurately quantify the carbon storage potential of this technology. Because biochar composition and structure depend on the biomass feedstock and process by which it is produced, quantitative assessments should be coupled with promising biomass-to-fuel conversion processes.

Carbon Negative Pathways

A range of thermochemical conversion pathways for converting biomass to fuels has been developed, including gasification, pyrolysis, hydropyrolysis, and hydrothermal liquefaction. Currently, none of these pathways has net negative life cycle carbon emissions; however, most technology developers optimize processes for maximum fuel production, not carbon emissions—often burning co-produced biochar to provide low-cost process heat. Research is needed to optimize existing biomass-to-fuel processes and to develop new pathways for net carbon negative emissions. Emphasis should be on robust processes and that can utilize a multitude of biomass feedstocks to maximize their long-term commercialization potential as well as enabling subsystem technologies that reduce the overall costs of carbon negative biomass-to-fuel processes.

Component 4. Biomass-to-Fuel with Carbon Capture

Carbon Negative Pathways

At the time of this study, biological pathways for converting lignocellulosic biomass-to-fuels appears to be the most speculative carbon removal approach. The fundamental problem is the recalcitrance of lignin and the inability of organisms to metabolize it. Consequently, most integrated lignocellulosic biorefineries burn their lignin for process heat and power. Because lignin constitutes about 30 percent of the weight and 40 percent of the energy content of all biomass, burning it severely limits the potential for a scalable carbon negative process. Nonetheless, the merits of producing a pure CO_2 stream during fermentation that can be easily captured and stored is sufficient motivation to warrant basic and applied research into net carbon negative biological pathways. Specifically, bioengineering research aimed at designing pathways to break down lignin and convert it into fuels should be conducted. Successful biological lignin valorization could completely transform the economics of biological biomass-to-fuel processes and their potential for carbon removal. Therefore, an ongoing applied research program to develop carbon negative biological conversion of lignocellulosic biomass into fuel, conducted at universities and national laboratories, and managed by DOE, is recommended.

Future Research Considerations

If BECCS technology is to be deployed at scale, additional research considerations will likely arise during its future implementation. Specifically, an efficient and coordinated supply and utilization system will be needed. The committee identified the following systems-level needs:

- The field requires spatially explicit optimization of biomass-to-fuel and power implementation to design optimal BECCS network configuration accounting for plant scale, location relative to biomass supply, competition for biomass supply, CO_2 transport network, and CO_2 and/or char sequestration sites.
- Integration of biomass power plants with an electricity grid that may have a high fraction of various renewable energy technologies (e.g., solar, wind) in the future will present challenges in terms of load following, requiring improved understanding and control over ramping and flexibility.
- Reductions in the capital cost and energy consumption of CCS are needed to improve economic and technical viability of BECCS, with particular attention paid to any challenges that biomass feedstocks may introduce for CCS.
- The quality and variability of CO_2 produced from biomass power plants and the impacts on carbon capture system components will need to be analyzed to understand long-term impacts on pipeline, wellhead, and subsurface equipment.
- Coherent policy and governance, such as emissions accounting when biomass supply is not collocated with consumption (e.g., different countries), is needed to promote biomass markets, and extension and outreach may be needed to encourage landowners to adjust crops and practices.

Implementation of the Research Agenda

Funding

Scale of Funding

The research agenda budgets for prototype development were estimated assuming a 1000 t/d dry biomass commercial-scale plant has a capital cost of about \$100 million, which for a 50 percent efficient power plant corresponds to capital cost of about \$900/kW electrical capacity—on par with the cost of natural gas combined cycle power plants. Then using the “2/3 law” for economies of unit scale:

$$k(c) = k(c_0)\left(\frac{c}{c_0}\right)^{\alpha}$$

TABLE 4.9 Estimated Bench, Pilot, Demonstration-Scale Plant Costs, Dry Biomass Capacities, and Technology Readiness Levels

Plant Scale	Bench	Pilot	Demonstration	Commercial
Technology Readiness Level	4-5	6	7-9	10+
Dry Biomass Capacity, $t \cdot d^{-1}$	1	10	100	1000
Fuel Power, MW	0.2	2.2	22	220
Capital Cost, $MM	1	5	22	100
Cost per Capacity, $MM/($t \cdot d^{-1}$)	1	0.5	0.2	0.1

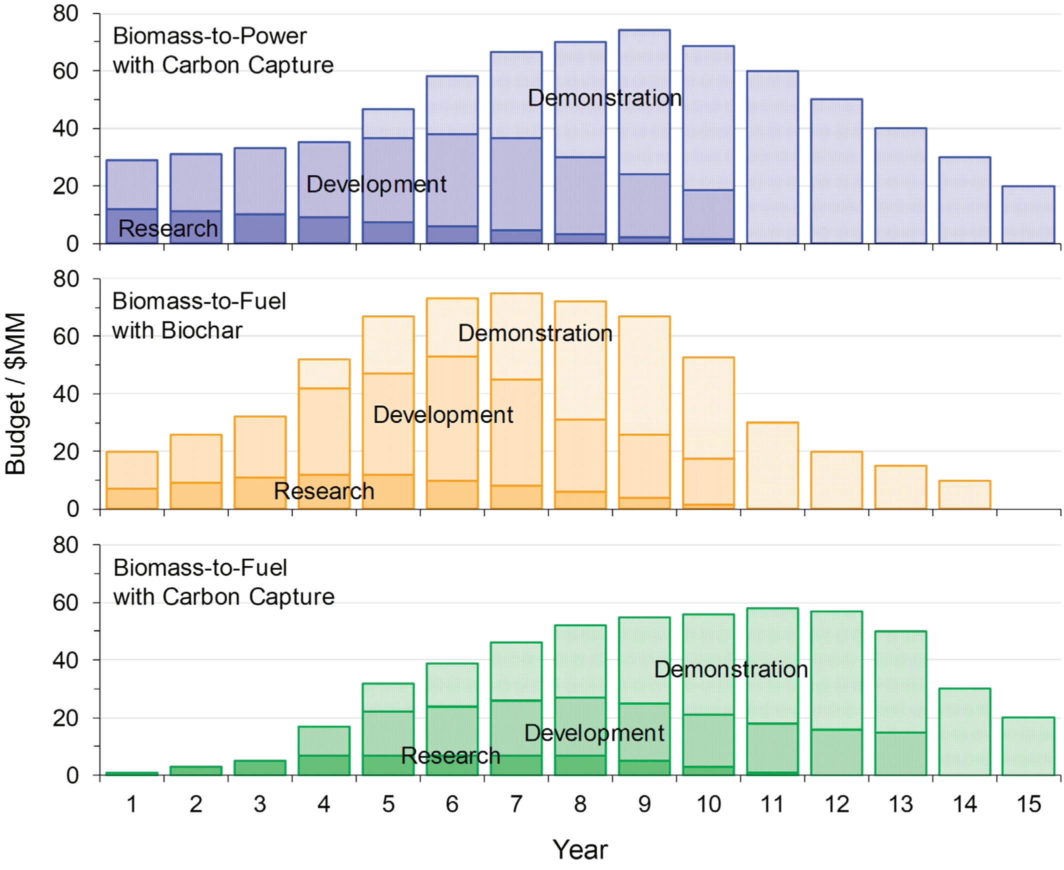

FIGURE 4.10 Illustrative research agenda budgets per year showing possible sequencing for biomass-to-power with carbon capture (top), biomass-to-fuel with biochar (middle), and biomass-to-fuel with carbon capture (bottom) pathways.

where k is the plant capital cost ($), c is the plant capacity (t/d), c_0 is the reference unit capacity, and α is the scaling factor of 2/3; an order-of-magnitude cost was estimated for bench, pilot, and demonstration-scale prototypes, Table 4.9.

Sequencing of Funding

The research agenda budgets for development of bioenergy with carbon capture technology are intended to be staggered over a period of 15 years. This approach should reduce technology and financial risk. Figure 4.10 provides an example of this sequence of research funding for each of the three BECCS pathways for the research agenda.

Sources of Funding

Though not explicitly called out in the research agenda, it is generally assumed that most of the funding will come from the federal government. That said, for more mature technology development projects it would not be unreasonable to expect industry participants to provide some or even all project funding. Although the funding of this research agenda falls outside the scope of this study, mechanisms other than traditional federal instruments for funding R&D, such as market-based policy incentives, warrant exploration.

Institutional Structures

Several federal agencies are capable of effectively conducting most of the proposed basic and applied research components and tasks, the most active being USDA, DOE, and EPA. Although programs within these agencies are well suited to conducting basic and applied research, they may not be well equipped to effectively run a technology demonstration program. In the past, public-private partnerships have played a critical role in the demonstration and deployment of new technology. For example, the Electric Power Research Institute (EPRI) and the Gas Research Institute (GRI) received their funds from taxes on interstate transmissions (electricity and gas) until utilities deregulation phased out this funding mechanism in the 1990s. In the absence of such organizations, Deutch (2011) proposed the creation of a new institution that would be responsible for managing and selecting technology demonstration projects and that would be supported by, but separate from, the federal government, which he called "the Energy Technology Corporation." This organization would house a well-designed technology demonstration program with the appropriate authority, tools, and expertise to accelerate technology development. The evaluation of existing technology demonstration capabilities with federal agencies and the investigation of institutional structures that will have the necessary capabilities to effectively develop and demonstrate new biomass energy technology is necessary to ensure successful scale-up and deployment of new technologies.

Research Management

The governance of a technology development program that includes demonstration of pilot prototype systems require engineers with industrial experience as well as standards for managing and evaluating new processes. NETL's CCS program serves as an example of a recent program implemented by the federal government.[4] NETL developed a standard methodology for assessing the cost of carbon capture from coal power plants and corresponding impacts on electricity costs. In addition, it developed a comprehensive technology development roadmap that spanned basic research to demonstration-scale plants.

The development of pilot and demonstration-scale process evaluation standards is essential for the effective governance of biomass energy technology development. These standards include process design engineering, equipment costing, and techno-economic analysis. Once a standard design basis has been developed, the use of third-party, independent, for-profit process engineering and estimating firms to provide technology assessments and techno-economic analyses is the most cost-effective way to vet new biomass energy processes. These technology evaluations should be made available to the public and how results were obtained transparent.

Carbon Accounting and Monitoring

One practical challenge to implementing any carbon removal technology is the accounting and crediting for carbon removal. By contrast, CO_2 emissions from the combustion of fossil fuels is straightforward and easily accounted for using existing reporting on fossil fuel extraction, imports, and sales. For biomass energy carbon removal approaches, carbon accounting is particularly challenging because the amount of net carbon removal largely depends on the specific pathway chosen (i.e., production,

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[4] See https://www.netl.doe.gov/research/coal/carbon-capture/carbon-capture-program (accessed January 28, 2019).

transport, conversion, sequestration). Policy research may be necessary to identify methods that provide a simple and fair system to track net carbon removal.

Monitoring the impacts of increasing biofuel production on land area and leakage, as well as CO_2 accumulation rates on land used for biofuel, are essential aspects of program implementation. Research needs that build on existing land monitoring programs are covered in Chapter 3. Likewise, the need to monitor the leakage of sequestered carbon gases from CCS is covered in detail in Chapter 7.

SUMMARY

Developing and deploying carbon negative bioenergy technology that is sustainable, scalable, and commercially viable is a daunting task with many possible approaches, each with its own unique benefits and challenges. The committee has recommended a research agenda that attempts to group and prioritize the most promising of these approaches and to set a realistic path for researching, developing, demonstrating, and deploying commercial BECCS technology. This research agenda has four components: (1) integrated assessment modeling; (2) biomass-to-power with carbon capture; (3) biomass-to-fuel with biochar; and (4) biomass-to-fuel with carbon capture.

Biomass supply is the overarching concern and consideration for large-scale implementation of BECCS technology. Worldwide, full-scale BECCS deployment will require an additional 300-600 Mha of land (roughly equal to the area of Australia) for energy crops. In the United States, assuming 1 billion tons of biomass is needed, a sufficient supply could be achieved with energy crops, forest biomass, organic waste, and agricultural residues, but the associated GHG emissions and environmental impacts remain unclear. To accurately assess the impact of BECCS on net GHG concentrations and climate change, a model is needed with the following essential elements: (1) land-use change impacts, including long-term nutrient and productivity changes; (2) emissions related to biomass harvesting, processing, and transportation (supply-chain emissions); (3) combustion efficiencies and related emissions of different fuels (referred to as “fuel substitution”); (4) indirect impacts, such as changes in land use or reductions in timber product inventories because of increased biomass demand; and (5) emissions related to carbon capture, transport, and storage. In addition, the changes in albedo and other biophysical processes that alter how GHG affect the climate should be explored. Currently, no such comprehensive integrated assessment model exists. To accurately assess the impact of BECCS on GHG concentrations and climate change, research is required to build a holistic integrated assessment platform that incorporates the essential elements above, as well as albedo and other climate impacts.

Today's biomass-to-power plants suffer from an inability to sustain a consistent biomass supply, price, and composition and from low power plant efficiency, both of which present barriers to the deployment of carbon negative biomass-to-power with carbon capture. Therefore, the biomass-to-power with carbon capture research agenda focuses on (1) biomass supply and logistics through conversion of conventional pulverized coal power plants to pretreated biomass fuel and (2) next-generation high-efficiency biomass power generation. In the near-term, the development of pretreated biomass as a drop-in replacement for coal in conventional coal power plants will leverage existing fixed-capital investments (coal power plants), while creating a robust, distributed biomass fuel supply infrastructure able to support future, more efficient biomass power generators. In the long term, biomass-to-power conversion must be more efficient, so that this carbon removal approach can be cost-effective, sustainable, and impactful. To accelerate technology deployment, this research agenda calls for the development of bench, pilot, and demonstration-scale prototypes of the most promising biomass pretreatment and biomass-to-power conversion technologies.

Biochar is one of the most promising near-term commercially viable carbon removal approaches. However, emerging commercial thermochemical biomass-to-fuel with biochar processes seek to either (1) maximize the production of liquid fuel and minimize the biochar or (2) maximize biochar production for sale into niche, high-end, home garden markets and minimize production of liquid fuel. Several thermochemical processes may be commercially viable without a price on carbon and may have net negative carbon emissions, but not at the same time. However, if the economics of biochar co-production could be positively changed by definitively demonstrating that biochar soil amendments increase crop yields, technology developers could co-optimize for both fuel and biochar, potentially making their process net carbon negative. As such, one research aim is to quantify biochar permanence in soil and the impact on crop productivity. Another research aim is to optimize existing biomass-to-fuel processes for carbon removal and investigate completely new carbon negative pathways. To accelerate technology deployment, the research agenda calls for the development of bench, pilot, and demonstration-scale prototypes for the most promising carbon negative approaches, scaling the dry biomass capacity from roughly 1 t/d bench-scale to 100 t/d demonstration-scale.

Biomass-to-fuel with carbon capture (or biological conversion) pathways are the last potentially carbon negative biomass technology. However, biological conversion pathways have been determined to have low carbon negative potential because today's organism cannot effectively decompose lignin. In integrated biorefineries, lignin derived from biomass is typically burned for heat and power. Given that lignin represents about 30 percent by mass and 40 percent by energy content of all biomass, bioengineering pathways to break down and convert lignin to liquid fuels is specifically recommended. More broadly, only basic and applied research on carbon negative pathways is recommended for biological biomass conversion until a breakthrough is made in lignin valorization.

CHAPTER FIVE

Direct Air Capture

INTRODUCTION

The results of recent integrated assessment modeling (Fuss et al., 2013) have made clear the need to include negative emissions technologies (NETs) as one component in a portfolio of solutions (e.g., mitigation, energy efficiency, renewables, fuel-switching) to prevent greater than 2°C global warming by 2100. Among these NETs is the direct removal of carbon dioxide (CO_2) from the atmosphere, commonly referred to as direct air capture . To be considered a NET, direct air capture systems must sequester the captured CO_2 on a timescale that positively impacts climate change. Currently, the only reasonable approach to store captured CO_2 is geologic sequestration, which is covered in Chapter 7.

Direct air capture has received significant attention in the public media because it provides a means to reverse CO_2 emissions, appears to be a relatively "easy fix" to climate change, and is a relatively new and high-tech NET. In addition to negative emissions potential, direct air capture systems benefit from their inherent flexibility of placement, which can reduce the need for pipelines[1] from the capture site to the sequestration reservoir. Furthermore, direct air capture systems have the flexibility to produce CO_2 for the commodity market at a desired purity. However, thermodynamics sets a lower bound on the energy required to separate a mixture of gases. Dilute streams are more difficult to separate and require more energy than more concentrated mixtures. A discussion of the thermodynamic limitations appears in Appendix D. The direct air capture approaches described in this chapter are technically feasible, but because CO_2 in air is ~300 times more dilute than in flue gas from a coal-fired power plant, the separation process for the same end CO_2 purity will likely be more expensive than capture from fossil fuel power plants.

CO_2 removal from gas streams is an important component of many industrial processes. The choice of removal technology is governed by the concentration and pressure of the gas stream. Physical solvents are used at high concentrations in natural gas processing and chemical production. Lower concentrations require use of chemical

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[1] Approximate cost of CO_2 transportation via pipeline is \$2.24/tonne CO_2 per 100 km of dedicated pipeline (DOE, 2015a).

bases that react with CO_2, a Lewis acid. Among the simplest of these are hydroxides and amines. These can be introduced either as components of a liquid (usually aqueous) solution, or as functional groups on the surface of a high surface area solid material. Thus, CO_2 can be captured from dilute gas streams, including air at ~400 ppm CO_2, by contact with basic liquids and solids. However, capture is only the first step. For manufactured direct air capture systems[2], the capture agent, either liquid or solid, must be able to release CO_2 at conditions of temperature and pressure that are accessible with low energy input, so that the capture agent can be used repetitively, and to prepare CO_2 for some form of secure sequestration. Capture generally happens spontaneously using these chemical agents, and the most significant energy costs are incurred in the step that recovers and concentrates the captured CO_2. Capture is generally an exothermic process, and desorption for concentration is an endothermic process.

This chapter evaluates two types of direct air capture CO_2 separation processes: one employing liquid solvents and one utilizing solid sorbents. Material and energy balances are carried out and compared to quantify the net reduction of CO_2 from the atmosphere depending on the energy sources assumed (e.g., renewables, nuclear, natural gas, or coal). This analysis helps to identify the technical challenges of each capture process to inform development of a future research and development (R&D) agenda. A discussion and analysis of CO_2 compression, transport, and subsequent geologic sequestration are covered separately in Chapter 7 on Geologic Sequestration and Appendix F. This chapter also provides estimates of the annual CO_2 reduction potential, cost, and capacity associated with each capture process.

BACKGROUND

Economics (Literature Review)

The cost of carbon capture for direct air capture systems has been a contentious issue. The estimates found in the literature span an order of magnitude, from \$100 to \$1,000/tCO_2 (Ishimoto et al., 2017). These estimates represent the costs of CO_2 captured and not the costs of net CO_2 removed from the atmosphere, with these costs tending to render direct air capture among the most expensive atmospheric CO_2 removal approaches. One challenge to comparing estimates is that earlier reports

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[2] The focus of this chapter is on manufactured direct air capture systems, which utilize chemical or physical processes that are designed to capture CO_2 from the ambient air. These systems differ from those that rely on natural phenomena such as CO_2 uptake by plants or minerals in the natural environment.

often used different system boundaries; for example, not all studies accounted for all the steps needed for a complete cycle. Some utilized generic correlations for process operations, while others performed out detailed optimizations of specific systems. As progress continues on pilot and demonstration plants, more accurate costs can be expected to become available.

Estimates at the high end of the cost spectrum (\$1,000/tCO_2, House et al., 2011) were not based on a specific technology. Rather, they were based on direct air capture energy requirements and application of second-law efficiencies to the calculation of minimum separation energy based on 75 percent air capture and 95 percent CO_2 product. A range of energy resource costs from wind to natural gas were considered, leading to an approximate upper estimate of \$1,000/tCO_2.

Estimates of \$641-819/tCO_2 based on a benchmark liquid system were provided in the first report to assess direct air capture, produced by the American Physical Society (APS) (Socolow et al., 2011). Although comprehensive in its analysis, that report's benchmarking system introduced key limitations. This system conceptually adapted the technology for CO_2 capture from flue gas streams—countercurrent flow of gas and liquid caustic solutions in a packed column—to CO_2 capture from air. Because air has much lower concentrations of CO_2, the volume of gas flow per ton of CO_2 captured is much larger and the power requirements to overcome the pressure drop in the vertical packed tower configuration contribute to significant capital and operating costs. Although optimization of the operating conditions for this design could reduce costs somewhat (estimated as \$528-579/tCO_2 [Mazzotti et al., 2013] and \$309-580/tCO_2 [Zeman, 2014]) the basic geometry and gas-liquid contact scheme would remain the same. Such designs are now recognized as not broadly applicable to direct air capture systems.

As highlighted by several studies, altering the flow configuration to reduce pressure drop can dramatically reduce capture costs compared to the APS benchmark system, which is based on a more conventional approach that mimics post-combustion capture absorber technology. Holmes and Keith introduced a combination of a cross-flow scheme for the gas relative to the falling liquid and a novel scheme involving the co-capture of CO_2 from air combined with an oxy-fired natural gas regeneration in a carbonate-based capture system. This configuration led to estimates between \$336-389/t CO_2 (Holmes and Keith, 2012) and \$93-220/tCO_2 (Keith et al., 2018). For solid adsorbents, low pressure–drop configurations analogous to the "honeycomb" structure of monoliths for automobile catalytic converters and other ultra-low-pressure–drop configurations are preferred motifs (Realff and Eisenberger, 2012). These novel configurations will require further testing and demonstration to realize the lower price points.

Laboratory studies of processes based on both solid and liquid sorbents have tended to estimate lower operating costs. Examples include amine-functionalized sorbent processes estimated at \$82-155/t CO_2 (Kulkarni and Sholl, 2012), though this study only considered operating costs. Earlier cost estimates based on aqueous chemical capture designs were similar at \$60-145/t CO_2 (Stolaroff et al., 2008) and \$165/t CO_2 for a complete system excluding sequestration (Keith et al., 2006). However, caution should be taken when making comparisons across studies because the completeness of the system considered, and the purity of the CO_2 stream produced, vary among them.

Commercial Status

Several companies are currently working to commercialize direct air capture systems (Table 5.1). These companies are primarily focused on units that operate on the scale of 1 Mt/y CO_2 capture from the air and are primarily privately funded.

Many direct air capture systems have been proposed. These can be distinguished by characteristics including the choice of liquid solvent or solid sorbent, method for CO_2 release/capture (regeneration), and purity of the output CO_2 stream.

Although pure (> 99 percent) CO_2 is desired for geological storage or sequestration, more dilute streams containing 3-5 percent CO_2 can still be useful for supply to enclosed greenhouses and algae farms (Wilcox et al., 2017). Although commercial entities need to monetize CO_2 to offset R&D costs and grow their business, if CO_2 is separated from air for utilization, then it must be sequestered on a timescale that positively impacts climate to be considered a NET. Of the companies listed in Table 5.1, all but Carbon Engineering utilize capture by amine (or ammonium)-based solid sorbents, although some are considering other kinds of structured solid sorbents in their continued development. Carbon Engineering's process involves aqueous hydroxide solutions that react with CO_2 to precipitate a carbonate salt. Most approaches rely on heating or a combination of heat and vacuum to release captured CO_2 from its bound state on the solid sorbent or, in the case of the precipitate in the Carbon Engineering process, to thermally decompose the carbonate. The resulting alkaline oxide, or hydroxide in the latter case, is then re-dissolved in the aqueous solution, thereby restoring its CO_2 uptake capacity. Alternative methods of regenerating solid sorbents have been advanced by Wang et al. (2013), as well as companies such as Infinitree (humidity swing). In the latter case, after capture under relatively dry conditions, exposure of the CO_2-saturated sorbent to humid air under mild vacuum causes release of CO_2.

TABLE 5.1 Companies Working to Commercialize Direct Air Capture Systems

Company	System Type	Technology	Regeneration	Purity/ Application	Scale
Carbon Engineering	Liquid solvent	Potassium hydroxide solution/calcium carbonation	Temperature	99%	Pilot 1 t/d
Climeworks	Solid sorbent	Amine-functionalized filter	Temperature or vacuum	99% w/dilution depending on application	Demonstration 900 t/y
Global Thermostat	Solid sorbent	Amine-modified monolith	Temperature and/or vacuum	99%	1,000 t/y
Infinitree	Solid sorbent	Ion-exchange sorbent	Humidity	3-5% algae	Laboratory
Skytree	Solid sorbent	Porous plastic beads functionalized with benzylamines (Alesi and Kitchin, 2012)	Temperature	Air purification, greenhouses	Appliance

At the time of writing, all the companies have technologies that are either in the laboratory stage or have advanced to one-off pilot or demonstration plants. Climeworks has advanced the farthest, operating a 900 t/y demonstration plant in Switzerland where CO_2 is used for various applications, rather than stored in geologic reservoirs.

ANALYSIS: ENERGETICS, CARBON FOOTPRINTS, AND COSTS

This section presents the Committee's analyses of the energetics, carbon footprints, and economics of direct air capture systems based on liquid solvents and solid adsorbents. Both analyses were based on the following ***baseline assumptions***:

- Plant capture rate from air = 1 Mt/y CO_2
- Concentration in air = 400 ppmv CO_2
- Volumetric flow rate ≥ 58,000 m^3/s air
- Capture fraction from air ≥ 60+ CO_2
- Concentration of product ≥ 98 percent CO_2
- Emission factors
    - Heat from natural gas = 227 g CO_2/kWh
    - Heat from coal = 334 g CO_2/kWh
    - Heat from nuclear = 4 gCO_2/kWh

  - Heat from solar = 8.3 gCO_2/kWh
  - Electricity from grid (U.S. average) = 743 gCO_2/kWh
  - Electricity from natural gas = 450 gCO_2/kWh
  - Electricity from coal = 950 gCO_2/kWh
  - Electricity from nuclear = 12 gCO_2/kWh
  - Electricity from solar = 25 gCO_2/kWh
  - Electricity from wind = 11 gCO_2/kWh
- Plant life = 10 years[3]

When designing a plant capable of capturing 1 Mt/y CO_2 from the air, one has to carefully consider the energy resources that will power the plant to determine the net removal of CO_2 from the air. For instance, if fossil fuels supply the energy in the absence of conventional carbon capture and sequestration (CCS), the net removal of CO_2 from the air may be significantly reduced. When comparing the costs of direct air capture across varying boundary conditions, the estimates for direct comparison can be aligned through the use of a cost factor, represented by:

$$\text{Cost Factor} = 1/1\text{-}x$$

such that x is the CO_2 emitted per CO_2 captured. As x approaches 1, or for every ton of CO_2 captured, 1 ton is released, the factor approaches infinity, as does the cost. In contrast, as x approaches zero, the cost of net CO_2 removed becomes closer to the cost of capture. Examples of technologies that may lead to an x near zero are those that use low-carbon energy resources to supply the required heat and power to operate the system, which may be unique for a given direct air capture approach. For example, the liquid solvent approach requires temperatures of up to 900°C for regeneration. Technologies that may achieve this temperature include concentrated solar power towers (DOE, 2013), combustion of low-carbon hydrogen, PV or wind-sourced electric heating, and alternative designs of nuclear including high-temperature gas-cooled reactors (Harvey, 2017). In comparison, the solid sorbent–based approach requires significantly lower temperatures for regeneration (i.e., < 150 °C). Hence, the options for providing low-carbon energy differ but may include geothermal and light water nuclear reactors. It is also important to consider the embodied emissions of the materials required to build a plant capable of operating at 1 Mt CO_2 per year. Although the embodied emissions are not included in the current analyses, the amount of steel and cement for these plants may be nonnegligible. The current analysis makes clear that direct air capture, if fueled by low-carbon energy pathways, will have the greatest impact. However, fueling direct air capture plants with low-carbon energy resources in

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[3] Same as used by the U.S. Department of Energy for baseline power plant studies, such as in Draucker et al., 2010.

place of using those resources to directly replace fossil fuel–based point-source emitters requires careful consideration.

The design of both direct air capture approaches included an air contactor and regeneration facility. In general, a practical process requires five key attributes: (1) *low-cost air contactor* to allow for a contactor area that is large enough to minimize pressure drop, because the low concentration of CO_2 in air requires passage of large gas volumes through the contactor; (2) *optimal* CO_2*-sorption thermodynamics,* which relates to having a sorption isotherm with suitably high CO_2 uptake at CO_2 partial pressures below 500 ppmv to minimize sorbent inventory and overall size of the process. The need for high CO_2 uptake at low partial pressures suggests that sorbents need strong, chemical interactions with CO_2, in contrast to separation processes that operate at higher CO_2 partial pressures, where sorbents employing weaker, physical interactions may be used; (3) *rapid sorption/desorption kinetics*, which results in fast sorption and desorption, faster cycling, and therefore less sorbent needed for the same output; (4) *low sorbent regeneration energy* so that the CO_2 binding energy is high enough to achieve a good uptake capacity, but not so high that endothermic sorbent regeneration energy requires unacceptably high regenerator costs. Furthermore, effective process designs will minimize the thermal mass of equipment that is repeatedly thermally cycled between sorption and desorption—that is, the sensible heat of the process should be minimized; and (5) *low capital costs,* which applies to virtually any process but is particularly relevant for direct air capture systems, with the lifetime of sorbent media posing a potentially important capital cost for some designs.

The committee followed different approaches to analyze the liquid solvent and solid sorbent direct air capture systems described below. The *liquid solvent systems* analysis is derived from a conceptual process design published by Carbon Engineering (Holmes and Keith, 2012; Keith et al., 2018). The committee conducted its analysis before Keith et al. published in 2018, but after careful examination of that work, determined that its analysis aligns closest with the design "C" configuration, which omits the onsite power island and instead uses grid electricity to supply all electrical work, suitable in regions with available low-carbon electricity. However, the C configuration assumes compression of CO_2 to 15 MPa, and compression is not included in the committee's analysis. Compression results in an energy of 0.48 GJ/tCO_2 and cost of \$8/tCO_2, assuming an electricity cost of \$60/MWh—leading to additional emissions of 0.1 Mt CO_2 for every Mt CO_2 captured, assuming an average grid emissions factor of 744 kgCO_2/MWh.

In particular, for the regeneration of Carbon Engineering's capture material, the heat is sourced by burning natural gas in an oxygen-fired kiln in which CO_2 is produced by both the combustion of natural gas and the calcination of $CaCO_3$, the material that is partially responsible for removing CO_2 from the air. The committee's analysis of this process considers the overall energetics and economics of the combined process, as well as that obtained by direct air capture only, excluding the CO_2 produced from fossil fuel combustion. Several companies are pursuing *solid sorbents systems* (e.g., Climeworks, Global Thermostat, and Skytree), each developing their own unique proprietary process with different design features. Therefore, rather than analyzing a specific process, a generic sorbent-based process is considered, and key process parameters varied to provide a range of energetic and process costs.

Liquid Solvent Systems

Process Description

The two major components of a liquid solvent direct air capture process are the air contactor and regeneration facility (Figure 5.1). In this process, an aqueous potassium hydroxide solution (KOH) reacts with the CO_2 from the air to form water and potassium carbonate (K_2CO_3) in an air contactor. The potassium carbonate aqueous solution is then fed to a causticizer, where it is reacted with calcium hydroxide ($Ca(OH)_2$) to form calcium carbonate ($CaCO_3$) precipitate. The $CaCO_3$ slurry is then fed to clarificatory and filter press to remove water, before it is fed to a calciner where the $CaCO_3$ precipitate is heated with natural gas in an oxy-fired kiln to about 900°C thereby producing solid calcium oxide (CaO) and high-purity CO_2 gas that can be compressed and transported for long-term sequestration.

Unit Operations

Air Contactor

The air contactor is used to contact the air with a KOH aqueous solution such that CO_2 reacts to produce K_2CO_3:

$$2KOH + CO_2 \rightarrow H_2O + K_2CO_3$$

The ambient air enters the contactor at 400 ppm and exits with 75 percent CO_2 captured in the solvent as K_2CO_3. Because of the high stability of this product species, a caustization step is required to react K_2CO_3 with $Ca(OH)_2$ to form calcium carbonate $CaCO_3$, regenerating the KOH solution for reuse in the contactor.

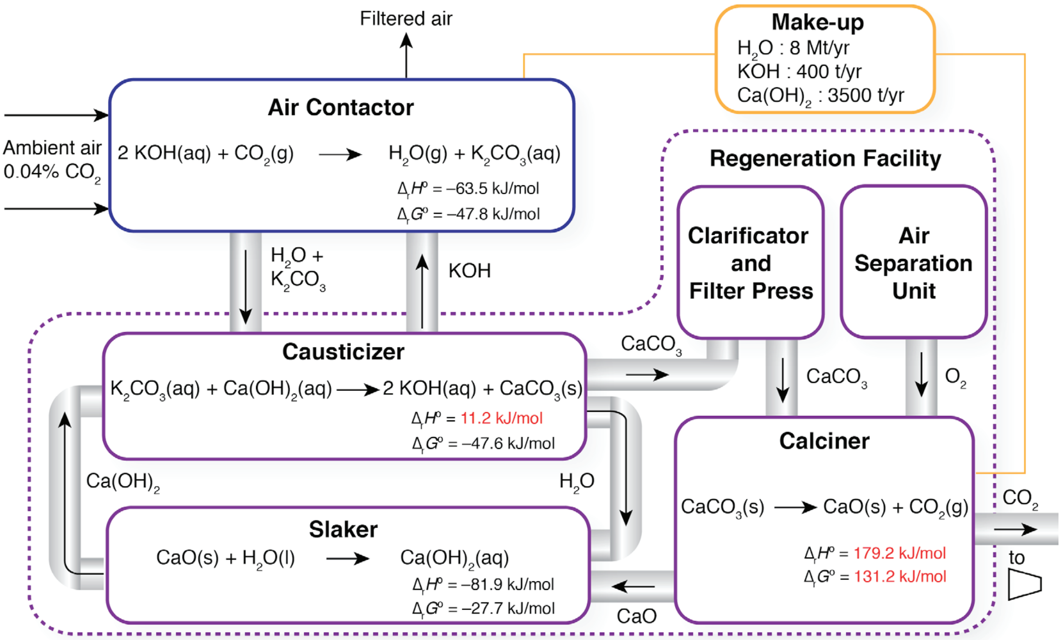

FIGURE 5.1 Simplified process flow diagram of a generic liquid solvent–based direct air capture system.

Contactor Sizing: In the air contactor, air is blown using fans over PVC-based packing material like that used in industrial cooling towers, as depicted in Figure 5.2. The solvent is a 1 M KOH aqueous solution that is sprayed uniformly over the packing material. The packing material assumed is Brentwood XF12560. Holmes and Keith (2012) determined that a capture fraction of 0.75 CO_2 in air was optimal based on their solvent-based separation process. With an air velocity of 1.5 m/s and 75 percent CO_2 capture from air, the contactor area needed to separate 1 Mt/y CO_2 is 38,000 m^2. The largest commercial packed towers have areas of about 100 m^2, which would indicate the need to construct hundreds of towers to achieve 1 Mt/y CO_2. Because of this challenge, Holmes and Keith have proposed adopting technology used in large-scale cooling towers and waste treatment plants. Their optimal air contactor design is approximately 20 m × 8 m × 200 m, and 10 contactors would be needed to capture 1 Mt/y CO_2, a considerable improvement over a conventional packed tower. Moreover, the packing volume for their system is estimated at 20,000 m^3, compared to a large cooling tower volume of 10,000 m^3 and a conventional packed tower of about 285 m^3. These considerations highlight that an optimized direct air capture contactor design will significantly differ from that of a conventional coal or natural gas post-combustion carbon capture plant.

Pressure Drop: When calculating the pressure drop, one has to consider the packing material composition (e.g., metal, plastic, ceramic) in addition to the nature of the air flow through the wetted packing material. For post-combustion applications, the flow is often modeled as counter-current (Mazzotti et al., 2013; Socolow et al., 2011), while in the work of Keith et al. (2012, 2018) it is modeled in a cross-flow configuration. The literature provides several pressure-drop correlations for conventional metal packing material with counter-flow configurations, but does not appear to do so for pressure-drop correlations for the PVC packing material with the cross-flow configuration as described in Keith et al. (2012, 2018). For this reason, in the Committee's analysis, a range in fan power energy consumption is established by considering separately the pressure drop associated with stainless steel and PVC packing materials. In the work of Keith et al. (2012, 2018), the pressure-drop across the packed tower is based on the following correlation developed specifically for the PVC packing material, Brentwood XF12560:

$$\Delta P = 7.4 D v^{2.14}$$

where ΔP is the pressure drop in (Pa), D is the column depth in (m), and v is the air velocity in (m/s). Based on Holmes and Keith's design ($v = 1.5$ m/s, $D = 6$–8 m), the resulting pressure-drop $\Delta P = 106$–141 Pa (1.0-1.4 mbar).

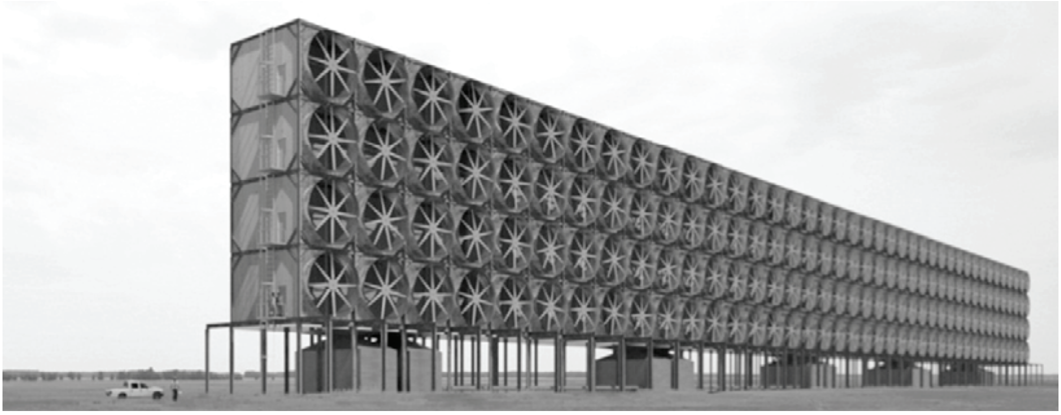

FIGURE 5.2 Conceptual drawing of the air contactor for a liquid solvent direct air capture system.
SOURCE: Holmes and Keith, 2012.

Mazzotti et al. (2013) showed that a novel, stainless steel packing material designed specifically for post-combustion capture may achieve a $\Delta P = 380$ bar ($v = 2.57$ m/s, $D = 3.6$ m). This pressure drop was derived for a counter-current flow contactor where air velocity and capture fraction were treated as optimizable variables. Implications behind the choice of packing material will be discussed in greater detail in the process economics section.

<u>Fan Work</u>: From the pressure drop, the fan power (MW) required to drive 58,000 m^3/s flowing air through the contactor can be calculated from:

$$\dot{w}_{fan} = \frac{\dot{V}\Delta P}{\varepsilon}$$

where $\dot{V}$ is the volumetric flow rate (m^3/s) and ε is the fan electrical efficiency (60 percent assumed). This yields an air contactor fan work = 10-37 MW. Thus, for a carbon capture rate of 1 Mt/y CO_2, the fan energy required is 0.32-1.18 GJ/t CO_2 (14.2-52.5 kJ/mol CO_2) captured. This equates to 0.073-0.269 Mt/y CO_2 emissions from coal-fired power and 0.044–0.160 Mt/y CO_2 from natural gas-fired power, resulting in an average annual net CO_2 capture of 0.83 Mt/y and 0.90 Mt/y for coal and natural gas power to the fan, respectively.

<u>Water Loss</u>: Depending on the molarity of the hydroxide solvent and the relative humidity, the water loss in the air contactor could be 1-30 mol/mol H_2O per CO_2 captured. Stolaroff et al., 2008 showed that increasing the concentration of hydroxide resulted in less water loss. Specifically, water loss was nearly eliminated for a ~ 7.2 M NaOH at 15°C and 65 percent relative humidity. However, Holmes and Keith (2012) estimated the minimum hydroxide concentration to mitigate water loss was 2 M KOH. Stolaroff et al., 2008 showed that a water loss of 20 mol/mol H_2O per CO_2 captured is typical for low concentration hydroxide solutions (e.g., 1.3 M) at 65 percent relative humidity. Thus, a liquid solvent direct air capture system with a 1 Mt/y CO_2 capture rate will require the addition of about 8.2 Mt/y water to make up for water loss.

Solvent Pump

To calculate the work required to pump KOH for even distribution across the packing material, the pressure drop, volumetric flow rate, and liquid density are required. This information was not available for the system of Holmes and Keith (2012), but they presented a rule of thumb in that the energy required for fluid pumping is approximately 15 percent of that required of the fan energy. This equates to 0.048-0.065 GJ/t CO_2

(2.13–2.84 kJ/mol CO_2) captured. The additional CO_2 generated by using coal or natural gas to generate electricity for solvent pumping results in 0.013 and 0.0077 Mt/y CO_2, respectively.

Slaker

In the slaker, CaO reacts with H_2O exothermically to regenerate $Ca(OH)_2$, which is reused in the causticizer:

$$CaO + H_2O \rightarrow Ca(OH)_2$$

Inert grit may be produced in the slaker, which impacts the efficiency of this step. Grit production depends on particle size, temperature, and the type of equipment used (Hassibi, 1999). Work for the slaking process has been estimated at 0.005 GJ/t CO_2 (0.2 kJ/mol CO_2) (Baciocchi et al., 2006), while efficiencies in the literature range from 0.95 to 0.99 (Emmett, 1986). Using an average efficiency, slaking work contributes additional emissions of 0.001 and 0.0007 Mt/y CO_2 when the electricity is sourced from coal and natural gas, respectively. Despite the exothermic nature of the slaking reaction and heat exchange that occurs between the slaking and causticization steps, this low-grade heat may not be easily integrated and becomes difficult to consider in the cumulative energy for regeneration.

Causticizer

In the causticizer, an K_2CO_3 aqueous solution is pumped from an exit stream in the air contactor and reacted with $Ca(OH)_2$ to make $CaCO_3$ and regenerate KOH for reuse in the air contactor:

$$H_2O + K_2CO_3 + Ca(OH)_2 \rightarrow 2\ KOH + CaCO_3$$

Typical causticization efficiencies for sodium hydroxide (KOH efficiencies are lacking in the literature) range from 0.8 to 0.9, which means that energy requirements will increase to account for the additional processing needed to compensate for nonideal conversions (Mahmoudkhani and Keith, 2009). However, the causticization step has negligible work requirements compared to other steps in the regeneration cycle (Baciocchi et al., 2006); thus, incremental changes in work due to causticization efficiency are manifested in downstream processes (e.g., clarification and filter press).

Following the causticization reaction, the supernatant KOH (aq) solution is clarified, mixed with additional reclaimed solvent and pumped back to the absorber. The required work in the clarification step is estimated to be 0.109 GJ/tCO_2 (4.8 kJ/mol CO_2) assuming ideal conversion efficiencies in upstream processes (Baciocchi et al., 2006). Adjusting this work value for realized slaking and causticization efficiencies results in emissions of 0.025 and 0.015 Mt/y CO_2 for coal and natural gas, respectively. Precipitated $CaCO_3$ is filtered, thickened, and pressed in preparation for transport to the kiln for calcination. Heating and drying of the $CaCO_3$ is necessary to remove as much water content as possible before passage to the energy-intensive calcination step. This preparation is also energy intensive, requiring an estimated 3.18 GJ/tCO_2 (140 kJ/mol CO_2), or the equivalent of 0.30 and 0.20 Mt/y additional CO_2 emissions using heat derived from coal and natural gas, respectively.

Calciner

Following filtration, clarification, and drying, $CaCO_3$ must be heated to high temperatures (~ 900°C) in a calciner to form calcium oxide (quicklime) and highly concentrated CO_2:

$$CaCO_3 \rightarrow CaO + CO_2$$

After calcination, the quicklime is returned to the slaker, where it reacts with water exothermically to regenerate $Ca(OH)_2$ and heat the slaking solution to about 95°C (Baciocchi et al., 2006). Although low-grade heat such as this is often difficult to integrate, a separate $CaCO_3$ steam drying process using heat recovered from lime hydration could offset thermal requirements for drying by 2.39 GJ/t CO_2 (105 kJ/mol CO_2) (Zeman, 2007). In addition, calcination efficiencies of over 0.9 have been reported in the literature (Martinez et al., 2013; Stamnore and Gilot, 2005). Heat requirements reported in the literature (Baciocchi et al., 2006; Zeman, 2007) for the calcining process range from 6 to 9 GJ/tCO_2 (264-396 kJ/mol CO_2). This includes an efficiency factor of 0.75 for the direct use of thermal energy.

Because of this large thermal requirement, CO_2 emissions associated with traditional calcination processes are significant, ranging from 0.38 to 0.57 and 0.56 to 0.84 Mt/y CO_2 for natural gas and coal firing, respectively. To minimize CO_2 generated in the direct air capture process, any thermally generated CO_2 could, in theory, become co-captured with that from ambient air. However, the balance of post-kiln exhaust is largely nitrogen, and if the end goal is to produce a near-pure (≥ 99 percent) CO_2 stream, then additional CO_2 separation equipment is required. Oxygen-fired (oxy-fired) kilns can obviate the need for additional CO_2 separation equipment, because they produce an exhaust that is composed of only CO_2 and H_2O, allowing the production of a near-pure CO_2 stream after the water is condensed out. For heat recovery from the calciner, a heat-exchanger is used to cool the 900°C flue gas exiting to 200°C with the incoming gas. Then, the 200°C flue gas is passed through a condenser and further cooled to 30°C. Pure oxygen for the oxy-fired kiln is separated from air using an air separation unit (ASU), where its electric requirements are 0.30 GJ/t CO_2 (13.2 kJ/mol CO_2), leading to a footprint of 0.068 and 0.041 Mt/y CO_2 using electricity-derived from coal and natural gas firing, respectively.[4]

Chemical Make-up

Reagent loss may occur at several points in a liquid solvent direct air capture process. Because of the nature of direct air capture, foreign contaminants may enter the absorber (e.g., insects, birds, particulate matter, sulphur oxides [SO_x] and nitrogen oxides [NO_x]) and then accumulate and combine with Ca-ions to form undesirable products. Further Ca-ion loss can occur during filtration and kiln firing. It is preferred to make up Ca-ion loss with $CaCO_3$ because of its relatively low cost ($200/t delivered) and smaller carbon footprint than other lime products, such as quicklime (CaO) and slaked lime ($Ca(OH)_2$).[5] In addition, KOH may be lost in the absorber through aerosol formation and spray drift (Keith and Holmes, 2012. Operational expenditures for chemical make-up have been estimated to be $0.90/t$CO_2$ captured (Socolow et al., 2011). Assuming this cost is split into $0.20/t$CO_2$ for KOH (aq) and $0.70/t$CO_2$ for $CaCO_3$(s), results in make-up requirements of 400 t KOH/y[6] and 3,500 t $CaCO_3$/y, respectively. Given that KOH is produced in the energy intensive chloralkali process (7 GJ/t KOH), make-up from KOH production yields a footprint of 590 t/y CO_2. Emissions from $CaCO_3$(s) make-up may be attributed to vehicle emissions from delivery (0.11 kg/t-mile CO_2), accounting for the round-trip, and any additional disposal required from waste buildup in the loop.[7]

Mass and Energy Balance

Estimated energy requirements for liquid solvent direct air capture systems are provided in Table 5.2 and depicted in Figure 5.3, and totals of 0.74-1.66 GJ/t CO_2 and

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[4] Based on 200 kWh per tonne O_2 produced in the ASU, and 0.56 mol O_2 per mol $CaCO_3$ supplied to the calciner.

[5] Emissions from $CaCO_3$ mining range from 1.5 to 80 kWh/t, resulting in negligible CO_2 emissions when compared to other steps outlined in this section.

[6] Based on a bulk purchase price of $506.5/t NaOH (Integrated Environmental Control Model [IECM]).

[7] This disposal may be considered analogous to reclaimer waste disposal in MEA regeneration ($260/t) (IECM).

9.18-12.18 GJ/t CO_2, for electricity and thermal energy requirements, respectively. The fans, pumps, slaker, causticizer/clarifier, and air separation units are all assumed to run off of grid-sourced electricity, while the heater/dryer and calciner represent the thermal requirements of the overall system. As shown in Figure 5.3, collectively, the energy required from running the electric components of the system totals from 6 to 18 percent of the entire energy demand for the process. In particular, the dominant energy-intensive component of this process is the thermal regeneration of CaO and subsequent production of high-purity CO_2, followed by the step of heating and drying of $CaCO_3$. These steps collectively reduce the net CO_2 captured to between 0.11-0.42 Mt/y CO_2 if natural gas is used as the thermal energy source and 0-0.11 Mt/y CO_2 for coal. In other words, using coal as the thermal source results in nearly equivalent emissions of CO_2 as that captured. These estimates include a thermal credit of 1.5 GJ/tCO_2 from the cooling of the calciner exhaust unit. Because of the uncertainty associated with a well-defined system that could recover the heat generated from the hydration reaction of the steam drying process, this credit was not included in these estimates. This is also a primary difference between the analysis of the current work and that of Keith et al. (2018), because they assume significant heat integration resulting in an average thermal work requirement of 5.25 GJ/tCO_2 compared to the lower bound of 8.4 GJ/tCO_2 in the current work. Incorporating heat recovery methods as described in Zeman (2007), this requirement may be reduced to 6 GJ/tCO_2. However, given the lack of clarity about heat integration approaches in the open literature, they were excluded from the current study. Further, because the calciner is oxy-fired, this approach in particular co-captures the CO_2 from air in addition to that generated from burning natural gas for the heat source. Consideration of this particular approach reveals that an additional 0.38-0.57 Mt/y CO_2 can be *produced* at high purity along with that captured directly from the air.

Assuming an initial atmospheric concentration of CO_2 at 400 ppm at 25°C, the minimum work of capturing 75 percent of the CO_2 at 98 percent purity is 0.45 GJ/tCO_2 (20 kJ/mol CO_2). Based on the energy requirements outlined for liquid solvent direct air capture systems, the "real" work is 8.2-11 GJ/t, leading to an exergy efficiency[8] of 4.1-6.2 percent.

Process Economics

In assessments of the costs and benefits of direct air capture, an area of contention has been the broad range of costs reported in the literature. Comparing costs without

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[8] Exergy efficiency is defined as the ratio of minimum work to real work: W_{min}/W_{real}.

TABLE 5.2 Liquid Solvent Direct Air Capture System Unit Operation Energy Requirements and CO_2 Generation

		CO_2 Generated (Mt/y)	
Unit Operation	**Energy Required ($GJ/t\ CO_2$)**	**Natural Gas**	**Coal**
Contactor fans	0.32-1.18	0.044-0.160	0.071-0.095
Solvent pump	0.048-0.065	0.007-0.009	0.011-0.014
Slaker	0.005	0.0007	0.001
Causticizer/clarifier	0.109	0.015	0.028
Air separation unit	0.30	0.041	0.028
Heater/dryer	3.18	0.20	0.30
Oxy-fired calciner	6.0-9.0	0.38-0.57[a]	0.57-0.85[a]
Exhaust gas cooling	-1.5	-0.11	-0.15
Additional heat recovery[b]	-2.4[c]	—	—
Total (w/o gas cooling credit)	9.9-14	0.69-1.00	1.00-1.31
Total (w/ gas cooling credit)	8.4-12.5	0.58-0.89	—

[a] Emissions co-captured with those from ambient air.

[b] Heat recovered from hydration of CaO for use in $CaCO_3$ drying (Zeman, 2007).

[c] Neglected in process total.

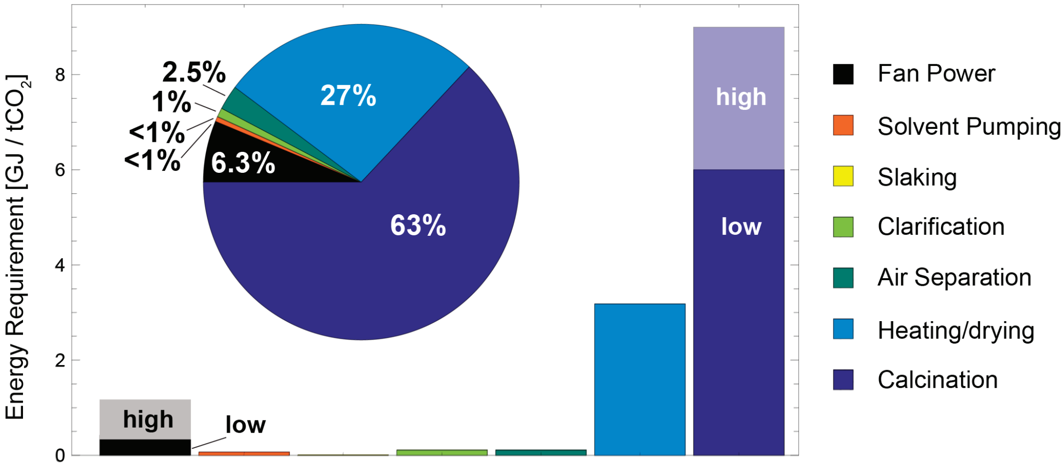

FIGURE 5.3 Estimated energy requirements for a liquid solvent direct air capture system using a calcium carbonate cycle, where most of the energy is for $CaCO_3$ preparation for calcination and CO_2 liberation in the kiln (calculated at 900°C).

first normalizing conditions and boundaries is misleading; thus, it is important to emphasize that the cost estimates presented here are for the separation and capture of CO_2 from ambient air from modestly optimized, generic direct air capture systems operating at 75 percent capture with highly concentrated CO_2 product (~ 98 percent purity), which is needed to minimize compression costs and volume requirements for geological sequestration. These cost estimates reflect the total annual economic penalty incurred for removing 1 Mt CO_2 from air on a per ton CO_2 captured basis. However, additional CO_2 emissions can be generated in several of the steps required in direct air capture systems. It is important to account for these emissions directly in the *avoided cost* expression by assuming a penalty for any emissions generated. This cost of CO_2 avoided is always higher than the cost of CO_2 captured and approaches infinity as the amount of CO_2 generated during capture approaches the amount captured. It is important to account for these emissions directly in the *net cost* expression by assuming a penalty for any emissions generated. This net cost of CO_2 removed is always higher than the cost of CO_2 captured and approaches infinity as the amount of CO_2 generated during capture approaches the amount captured. The cost estimates presented here also vary by energy source and do not include costs for compression, transportation, injection, and sequestration.[9]

The estimated capital and operating costs for a 1 Mt/y CO_2 liquid solvent direct air capture system are provided in Table 5.3. This cost analysis presents an optimistic scenario based on optimal parameters (for instance, Holmes and Keith [2012] and Keith et al. [2018]), where co-dependent parameters are jointly optimized to minimize system cost. Here, any literature values on installed equipment costs are taken directly, whereas direct equipment costs are multiplied by a 4.5 factor to convey total installed cost (Rudd and Watson, 1968). A realistic case is presented whereby parameters are set at their respective upper bounds as indicated in Table 5.3. A realistic worst-case scenario still aims to minimize cost through single- and joint-parameter optimization, but additional factors (e.g., higher cost of electricity, extent of heat integration, new technology multiplying factors, equipment quotes) elevate additional cost components, leading to a higher total cost. These estimates yield capture costs of \$147-264/tCO_2 for natural gas–fueled systems and \$140-254/tCO_2 for coal-fueled systems (Table 5.4). The estimated net costs per CO_2 removed are \$199-357/tCO_2 for natural gas–fueled systems and approach infinity in the case of coal-fueled systems, because more CO_2 is generated than captured.

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[9] Because costs for compression, transportation, injection, and storage for CO_2 captured both through bioenergy with carbon capture and sequestration (BECCS) and direct air capture are assumed to be approximately the same, the report discusses them once in Chapter 7 and again Appendix F.

TABLE 5.3 Estimated Capital (CAPEX) and Operating (OPEX) Costs for a Generic Liquid Solvent Direct Air Capture System with a Capacity of 1 Mt/y CO_2 Removal

CAPEX	**Cost ($M)**	**Comment**
Contactor array	210–420	*Lower bound:* reported cost of air contactor array from Holmes and Keith (2012), based on optimal percent capture of 75% and bed depth of 6-8 m and PVC packing material at ca. $250 /$m^3$. *Upper bound:* projected cost of re-optimized Keith and Holmes configuration using stainless steel packing ($1,500/$m^3$), shallow packing bed (3 m), and 1.5 × new technology cost factor.
Slaker, causticizer, clarificator	130–195	*Lower bound:* capital costs taken from Socolow et al. (2011) and adjusted to 2016 USD. *Upper bound:* 1.5× factor to account for new technology. Though the Ca-recovery cycle is mature and well studied in the pulp and paper industry, learning costs may be associated with integration into a direct air capture system.
Air separation unit and condenser	65-100	*Lower bound:* calculated from scaled CAPEX reported for air separation unit (ASU) in the integrated environment control model (IECM; Rubin et al., 2007) integrated gasification combined cycle (IGCC) process. *Upper bound:* 1.5 × factor applied for integration with calcination in direct air capture system. Condenser cost scaled from IECM estimate and assumed negligible ($300K) relative to ASU and other components
Oxy-fired calciner	270–540	*Lower bound:* price quote from industry source with 4.5 × factor used for scaling inside battery limits (ISBL) equipment costs to full costs (Socolow et al, 2011). *Upper bound:* calciner price quoted in Socolow et al. (2011), with 4.5 × factor applied. *Note:* one would need oxy-fired natural gas and coal kilns for each case, and commercial viability of these are unknown.
CAPEX Subtotal ($M)	675-1255	
CAPEX Annualized ($M/y)	81-151	Assumes a plant life of 30 years and fixed charge factor of 12%.

TABLE 5.3 Continued

OPEX	Cost ($M/y)	Comment
Maintenance	18-33	Range calculated as 0.03 of total capital requirement.
Labor	6-10	Range calculated as 0.30 of maintenance cost.
Makeup and waste removal	5-7	*Lower bound*: assumes \$500/t KOH, \$250/t $Ca(OH)_2$, \$0.30/t H_2O, \$260/t waste disposal (Rubin et al., 2007). *Upper bound*: applies 1.5 factor to make up OPEX.
Natural gas	25-35	Range calculated from low and high thermal requirements reported in Table 5.2, assuming natural gas cost of \$3.25/GJ.
Coal	18-25	Range calculated from low and high thermal requirements reported in Table 5.2, assuming 2016 U.S. average bituminous coal, \$48.40/ short ton, or \$2.33/GJ.
Electricity	12-28	Range calculated from electrical requirements reported in Table 5.2, with electricity price of \$60/MWh.
OPEX Subtotal (NG)	66-113	
OPEX Subtotal (coal)	59-103	

Although not accounted for in the current work, the compression of CO_2 would add on the order of \$8/tCO_2 to the cost of net removal, which enables comparison to costs reported in the literature that do account for compression (Keith et al., 2018; Mazzotti et al., 2013; Socolow et al., 2011). The cost of net CO_2 removed reported in the current work (\$490-880/tCO_2 removed) may be compared to the avoided costs reported in the APS study (\$641-819/tCO_2 avoided) and the related follow-up study of Mazzotti et al. (\$510-568/tCO_2 avoided). Mazzotti et al. considered three Sulzer packing materials: Mellapak-250 Y (also used in Socolow et al., 2011), Mellapak-500 Y, and Mellapak-CC, a novel stainless-steel packing material designed specifically for carbon capture. Optimization of the system around a specific packing material (Mellapak-250 Y) resulted in a 7 percent reduction in the avoided cost: \$610/tCO_2 (Socolow et al., 2011) vs \$568/tCO_2 (Mazzotti et al., 2013). Use of the advanced packing material (Mellapak-CC) resulted in an even lower avoided cost of \$510/tCO_2. Both Mazzotti et al. and APS assume a counter-flow configuration in the development of the pressure-drop relationship, which directly relates to the fan power required. This differs from that reported in Keith et al. (2018), which is based on a novel PVC-based packing material with a pressure-drop correlation assuming a cross-flow configuration. This

TABLE 5.4 Summary of Carbon Capture Costs for a Liquid Solvent Direct Air Capture System Powered by Natural Gas or Coal

Cost (\$/tCO_2)	Natural Gas	Coal
Capture cost[a]	147-264	140-254
Net-removed cost[b]	199-357	∞
Produced cost, oxy-fired calciner[c]	113-203	∞

[a] Basis = 1Mt net CO_2 removed from air.

[b] Basis = per net unit of CO_2 removed with an average of 0.3 Mt CO_2 for natural gas and zero for coal.

[c] Basis = per net unit of CO_2 *produced* including co-capture of CO_2 from natural gas oxy-fired kiln with an average of 1.3 Mt CO_2.

plastic packing is approximately one-sixth the cost of the metal packing assumed in APS and is expected to have a significantly lower pressure drop (ca. 10 pa/m) when compared to more commonly examined metallic packing materials (ca. 100 pa/m). If the plastic packing proves to be durable enough to withstand the caustic solvent over the life of the plant, the APS capital expenditure (CAPEX) estimate would decrease by nearly \$15/tCO_2 before considering system optimization. Additionally, a two-thirds reduction in operational energy expenditures on fan power may be achieved via the reduced pressure drop, resulting in an additional cost savings of \$7/tCO_2 assuming electricity from natural gas at \$60/MWh. This emphasizes the need for demonstration-scale projects in this field so that novel materials for packing, such as plastics coupled to unique configurations such as cross-flow, can be tested and verified.

An additional difference in the APS system design is the vertical absorber approach with an array of 330 squat scrubber towers with a total cross-sectional area of 37,000 m^2. Though quoted at 50 percent capture, the higher air velocity (2.0 m/s vs 1.5 m/s considered here) yields a cross-sectional area comparable to the system described in this report (38,000 m^2). However, the design of 330 squat towers is shown to be capital intensive with a total installed cost of \$1.3 billion—roughly 60 percent of the total system cost. Conversely, Holmes and Keith (2012) demonstrated a total installed cost of about \$150 million for an array of 10 air contactors with the design shown in Figure 5.2. Finally, the APS reported a calciner with an installed cost of \$540 million. However, industrial calciners with output compatible with 1Mt/y CO_2 capture systems may be purchased for about \$60 million, leading to a total installed cost of \$270 million—50 percent less than the cost reached by the APS study.

As previously discussed, Keith et al. (2018) suggest that these differences may be partially due to the design configurations, such as PVC packing coupled to a cross-flow configuration compared to metal packing coupled to a counter-flow configuration, with the former resulting in a lower pressure drop in addition to reduced capital expense in addition to the horizontal absorber design and extensive heat integration. Although new materials and configurations may result in reduced costs, without the opportunity to test them under realistic conditions (e.g., real environment and extended time), it will be difficult to realize the lower bounds of these cost estimates. The current work accounts for these previous studies (Keith et al., 2018; Mazzotti et al., 2013; Socolow et al., 2011) and provides a broad range of energies and costs that encompasses all of the steps in the solvent-based separation process. The broad range of energies and costs confirms the need for R&D in this space so that a true baseline cost for direct air capture may be established.

In addition to natural gas and coal resources for fueling the direct air capture plant, the committee also considered a low-carbon route based on solar photovoltaics (PV) and electrolytic H_2 to meet the power and heat requirements, respectively, in an attempt to minimize "x" in the cost factor of the equation on page 194. The committee also investigated an additional route based purely on solar PV with the assumption that an electric-fired kiln is used for the calcination process; the cost details are presented in Appendix D. Table 5.5 details the capital, operating, and maintenance costs based on this low-carbon scenario, which results in an average net removed CO_2 cost range of \$317-501/tCO_2.

In terms of the capital expense, the primary differences for this pathway is the replacement of an oxy-fired kiln with the H_2-fired kiln, the absence of an air separation unit, use of an electrolyzer for H_2 production, use of a compressor and pressurized storage tank for on-site H_2 storage, and the installation of PV modules, inverters, and battery storage for on-site electrical generation. The energy requirements for operating fans, solvent pumps, slaker, causticizer/clarifier, and gas cooling unit (see Table 5.2) are used as input parameters to determine the energy costs of PV solar, including battery storage so that the system operates continuously. Further, a water flow rate of 5.7×10^5 t/y H_2O is needed to produce an average of 4.15 kmol/hr H_2 to then produce the heat required for a direct air capture plant designed to remove 1 Mt/y CO_2. The energy required for electrolysis dominates the energy operating costs as shown in Table 5.5, followed by the H_2 compression energy required.

TABLE 5.5 Economic Costs Associated PV, Storage, and H_2-Fired Calciner for Solvent-Based Direct Air Capture

CAPEX	Cost ($M)	Comment
Contactor array	210-420	*Lower bound:* reported cost of air contactor array from Holmes and Keith (2012), based on optimal percent capture of 75%, bed depth of 6-8 m, and polyvinyl chloride (PVC) packing material at ca. $250/m^3. *Upper bound:* projected cost of re-optimized Keith and Holmes configuration using stainless steel packing ($1,500/m^3), shallow packing bed (3 m), and 1.5 × new technology cost factor.
Slaker, causticizer, clarificator	130-195	*Lower bound:* capital costs taken from Socolow et al. (2011) and adjusted to 2016 USD. *Upper bound:* 1.5 × factor to account for new technology. Though the Ca-recovery cycle is mature and well studied in the pulp and paper industry, learning costs may be associated with integration into a direct air capture system.
H_2-fired calciner	360-720	*Lower bound*: price quote from industry source for oxy-fired kiln with 6 × factor used for scaling ISBL equipment costs to full costs and to account for new technology. This may be too low due to the uncertainty of the commercial availability of a H_2-fired kiln. Efficiency of 95% assumed. *Upper bound*: calciner price quoted in Socolow et al. (2011), with 6 × factor applied to account for new technology.
Condenser	0.3	Condenser cost scaled from IECM estimate and assumed negligible ($300K) relative to other components.
Water	1.1	Water investment at $2/t at 3.6×10^3 - 4.7×10^3 kmolH_2/hr, 5.7×10^5 tonnes water required per year, assuming negligible losses.
Electrolyzer	260-420	Alkaline (mature) $850-1,500/kW; assuming HHV of 283.74 MJ/kmol H_2 (IEA, 2015b) giving electrolyzer power requirement of 310-525 MW.

TABLE 5.5 Continued

CAPEX	**Cost ($M)**	**Comment**
PV+battery	865-1465	Direct electricity needs, i.e., 33-73 kJ/mol CO_2 for direct air capture processing, 430-730 kJ/mol CO_2 for electrolyzer, and 51-68 kJ/mol CO_2 for H_2 compression. Assumes total installed cost of $\$2.2/W_{AC}$ including PV modules and inverter, with battery storage adding an additional $15/MWh (Fu et al., 2017).
Compressor	22-37	88% efficiency compression to 18MPa, $\$70/kW_{H2}$ (IEA, 2015b; Ogden, 2004).
Pressurized tank	73-207	$\$236\text{-}394/kW_{H2}$
CAPEX Subtotal	*1,921-3,045*	
Annualized Capital Payment ($M/y)	*230-365*	Assumes a plant life of 30 years and fixed charge factor of 12%.
OPEX	**Cost ($M/y)**	
Maintenance	58-91	Range calculated as 0.03 of total capital requirement.
Labor	17-27	Range calculated as 0.30 of maintenance cost.
Makeup (H_2O, KOH, $Ca(OH)_2$) and waste removal	5-7	*Lower bound*: assumes $500/t KOH, $250/t $Ca(OH)_2$, $0.30/t H_2O, $260/t waste disposal (Rubin et al., 2007). *Upper bound*: applies 1.5 factor to make up OPEX.
PV+battery	6.7-11.3	Assumed as $18/kWac (Fu et al., 2017).
OPEX Subtotal	*87-136*	
Cost = Avoided Cost (\$/tCO$_2$ yr^{-1})[a]		
PV+Storage+H_2-Fired	317–501	

[a] Basis = 1Mt CO_2

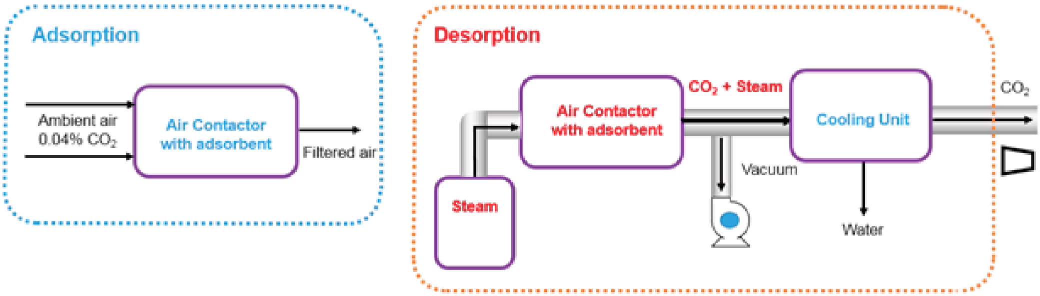

FIGURE 5.4 Schematic illustration of two-step, sorbent-based direct air capture process. NOTES: (1) Air contacts the sorbent using a gas-solid contactor (left) and (2) a heating the system with possible application of vacuum is used to desorb the CO_2 from the sorbent followed by cooling before returning to the initial state (right).

Solid Sorbent Systems

Process Description

Like liquid solvent systems, solid sorbent direct air capture systems have two main processes: adsorption and desorption that operate cyclically (Figure 5.4). In these systems, air is blown through a solid adsorbent contained within an air contactor, where the CO_2 in the air is adsorbed onto the solid adsorbent. Next, the solid adsorbent with CO_2 is exposed to heat and/or vacuum to liberate the CO_2 from the solid adsorbent. Finally, the solid sorbent is cooled before it is restarted.

Owing to the suitability of temperature swing adsorption (TSA) for capturing ultra-dilute species (Lively and Realff, 2016), the committee assessed a generic adsorption process employing either just TSA or TSA in combination with vacuum swing adsorption (VSA) to place probable bounds on energy consumption, CO_2 emissions, and associated costs for solid sorbent systems.[10] This section describes a generic, hypothetical process, as well as its estimated energy use and consequent CO_2 emissions.

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[10] Such a process does not map to the humidity swing approach employed by Infinitree, as outlined in Table 5.1.

Unit Operations

Adsorption

Air is blown through a solid structure (contactor) that contains a suitable CO_2-adsorbing material and CO_2-depleted air is emitted from the process. In the adsorber, the main contributor to energy use is the electrical energy required for fans to drive air through the contactor containing the solid sorbent. The primary driver for the energy consumption associated with this step is the pressure drop through contactor. This part of the process deviates substantially from the more often studied flue gas separations.

Desorption

After the solid sorbent has been saturated with CO_2, it is moved to the desorber[11] where heat (TSA) or heat and vacuum (TSA/VSA) systems are used to desorb CO_2 (regeneration) and produce a concentrated CO_2 stream. Regeneration is the most energy-intensive step for a solid sorbent direct air capture system and includes the thermal energy needed to induce CO_2 desorption (ΔH_{ads}) and heat up the sorbent, contactor and other equipment (ΔH_{sens}), as well as electrical energy needed for vacuum pumps (if employed). Energy consumption in the condenser is deemed negligible, although some heat could be recovered if integrated into steam generation, and is therefore not considered in this analysis. Overall, the energetics for this energy-intensive step of the process are the same as for a similar regeneration step in a process targeting a more concentrated feed (e.g., capture from flue gas). Because of the energy intensity, process design innovations for this desorption step can have a large impact on the overall process efficiency. Designs that give rapid heat transfer, as well as minimize the CO_2 partial pressure over the adsorption media, are advantageous, providing both concentration and thermal driving forces for CO_2 desorption.

Mass and Energy Balance

In general, solid sorbent system designs aim to (1) minimize pressure drop for flow through the air-sorbent contactor; (2) minimize contactor mass while maximizing sorbent mass (thus minimizing the sensible heat energy losses); (3) maximize the CO_2

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[11] Or the adsorber is switched into desorption mode, if a single unit is deployed.

uptake; and (4) advantageously manage the water uptake.[12] For the generic process considered here, key process parameters were varied within a physically realistic range (Table 5.5). Adapting Realff and Kawajiri's methodology (Sinha et al., 2017), the committee estimated individual contributors to the energy consumed in the process and the cost of CO_2 capture.

Estimated process energy intensities for the generic solid sorbent direct air capture system were obtained by varying each parameter within the range provided in Table 5.6. The calculated thermal and electrical energy requirements are reported in Table 5.7, with the associated CO_2 emissions if the energy were provided by coal, natural gas, nuclear, wind, or solar reported in Table 5.8 (NREL, 2013). The electrical energy consumption was costed at an average grid price ($0.06/kWh) and the thermal energy cost was derived by considering the extra steam that would have to be produced to replace the electrical energy delivered from the condensing turbine of a power plant (Sinha et al., 2017). The estimated energy consumption falls in a similar range reported for other processes in the literature (Figure 5.5, Broehm et al., 2015).

Because of the possibility for wide variation in parameters, the committee considered five scenarios that represent different degrees of process optimization and performance (i.e., best case, low, mid, high, and worst case). The combination of every best-case parameter results in the lower bound (1-best), a scenario that may be unachievable because of correlations among various parameters, where optimizing one may move another away from an optimum (using currently known materials and approaches). Similarly, there are many ways to design a poor process with very high energy consumption. This scenario (5-worst) is presented here as an example where all the most pessimistic values were used. These two cases are shown for completeness, although the committee does not expect practical operation at either extreme. More realistically, three estimates using parameters in the middle of the range are provided (2-low, 3-mid, 4-high), where the descriptive words refer to anticipated carbon emissions and energy consumption. The approach used for these calculations is described in Appendix H, along with the specific parameters for each case.

An advantage of many recent solid sorbent–based direct air capture processes is that they do not require high temperature thermal energy. In an ideal scenario, the electrical energy needs should be met with renewable energy, and the thermal energy

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[12] For many sorbents, water uptake should be minimized to minimize the amount of water that must desorbed from the sorbent in each cycle, and its associated energy penalty. However, some adsorbents may benefit from co-adsorbing water, because CO_2 uptake may increase, in which case water uptake must be managed advantageously. Water adsorption can also be managed to balance the production of fresh water as a coproduct.

used should be acquired from low temperature waste heat when such heat sources are suitable and available. Doing so helps to maximize net CO_2 removal. Furthermore, use of waste heat could provide important stepping stones for early installations to operate with more privileged economics, potentially offsetting the disadvantage of being early on the technology learning curve. Nonetheless, because deployment that impacts negative emissions on a global scale will require heat and power, in all scenarios considered in this chapter, the energy used is sourced exclusively for the direct air capture process, and no assumption of waste heat use is made.

For each step in the solid sorbent direct air capture process, the CO_2 emissions were evaluated under several scenarios, including providing the *electrical energy* from wind, solar thermal, nuclear, natural gas, or coal and *thermal energy* from solar thermal, nuclear, coal, or natural gas (Table 5.7). The calculated energy requirements suggest

TABLE 5.6 Model Parameters That Affect Estimated Performance of a Solid Sorbent Direct Air Capture Process

Parameter	Units	Range
Inputs		
Contactor to adsorbent ratio	kg/kg	0.10-4.0
Adsorbent purchase cost	$/kg	15-100
Adsorbent lifetime	y	0.25-5.0
Sorbent total capacity (at 400 ppm)	mol/kg	0.5-1.5
Desorption swing capacity[a]	mol/mol	0.75-0.90
Air velocity	m/s	1-5
Desorption pressure (VSA)	bar	0.2-1.0
Desorption final temperature (TSA)	K	340-373
Heat of adsorption (CO_2)	kJ/mol	40-90
Outputs		
Adsorption time	min	8-50
Desorption time	min	7-35
Mass transfer coefficient[b]	1/s	0.01-0.1
Pressure drop	Pa	300-1,400

[a] Fraction of CO_2 adsorbed that is desorbed and recovered as product.

[b] Lumped linear driving force coefficient accounting for all resistances, see Appendix D.

NOTE: Some parameters (inputs) were varied within a physically realistic range, based on literature reports, and outputs were calculated from the model.

TABLE 5.7 Estimated Unit Operation Energy Requirements for Solid Sorbent Direct Air Capture Systems

Step	Type	Energy Required (GJ/t CO_2)	
		Mid-Range (low-high, 2-4)	**Full-Range (best-worst, 1-5)**
Desorption heat (100°C sat. steam)	Thermal	3.4-4.8	1.85-19.3
Air contactor fans	Electrical	0.55-1.12	0.08-3.79
Desorption vacuum pump	Electrical	$(110\text{-}140) \times 10^{-4}$	$(4–910) \times 10^{-4}$
Total		3.95-5.92	1.93-23.09

that the *worst-case scenario (5-worst) would be unable to provide negative emissions under any scenario where fossil energy was used*, even those that use renewable energy for electricity, because of the extensive thermal energy requirements provided by fossil energy. However, even the worst-case scenario that provided negative emissions uses solar thermal or nuclear energy for operation. By contrast, most other scenarios are substantially carbon negative, with the more realistic estimates (2-low to 4-high) being negative even when coal was used to provide all the energy (0.47-0.74 Mt CO_2 emitted per Mt CO_2 captured). While the use of coal to power a solid sorbent direct air capture system is not likely, it provides a useful worst-case emissions scenario, providing an upper bound to the problem. In the near term, one could envision rapid deployment using natural gas to provide thermal energy. Such a scenario yields a process with acceptable negative emissions (0.29-0.44 Mt CO_2 emitted per Mt CO_2 captured). Negative emissions drop further when renewable electricity is used (Table 5.7) and further still when thermal energy is generated from renewable sources. Nuclear energy provides another low emissions option.

Like liquid solvent systems, solid sorbent systems have a minimum work rate of 0.45 GJ/tCO_2 to capture 60-75 percent CO_2 from air to a 99 percent pure CO_2 stream. Based on the energy requirements outlined for solid sorbent systems, the “real” work rate is 1.9-23.1 GJ/tCO_2, leading to an exergy efficiency range of 2-24 percent, with the middle-range scenarios (2-low to 4-high) being 7.6-11.4 percent.

Process Economics

As noted above, the cost estimates presented here are for the separation and capture of CO_2 from ambient air from modestly optimized, generic direct air capture systems operating at 65-75 percent capture with highly concentrated CO_2 product (~99 percent purity). These cost estimates reflect the total annual economic penalty incurred for removing 1 Mt CO_2 from air on a per ton CO_2 captured basis. Because additional CO_2 emissions can be generated in several of the steps required in direct air capture systems, the *net costs of* CO_2 *removed* are also presented. The cost estimates presented vary by energy source and do not account for compression, transportation, injection, and sequestration (see Chapter 7 on geologic sequestration). The estimated costs of CO_2 capture for the range of scenarios considered are provided in Tables 5.9 and 5.10.

The two main phases of the cyclic adsorption process are shown above in Figure 5.4. In the adsorption phase, air is contacted with a solid structure that contains a suitable CO_2-adsorbing material, with air depleted in CO_2 being the exit stream from the process. In this step, key contributors to the process cost include (1) the energy required to pass the air over or through the adsorbing material, (2) the cost of the adsorbent, and (3) the cost of the contactor and other equipment, such as the fans that provide airflow. For routine equipment, such as the blowers and vacuum pumps, a factor of 4 was applied to the purchase cost to represent the total installed cost. For more innovative components, such as the gas-solid contactor, a factor of 6 was applied. It is instructive to compare the capital cost for the air-sorbent contactor between the solvent and solid sorbent cases. For the former, the total capital cost for the contactor ranges from $210 million to $420 million. For the latter, the total cost ranges from $13 million to $84 million. Considering that the solid sorbent case has a 10-fold higher surface area per volume, the order of magnitude of these costs is similar.

In the desorption phase of the process, heat (TSA) or heat and vacuum (TSA/VSA) are applied to the system to induce CO_2 desorption and recover a concentrated product. This second step incurs substantially more operating costs, including costs associated with the energy needed to induce desorption (ΔH_{ads}), energy required to heat the sorbent, contactor, and other equipment (ΔH_{sens}), and energy necessary to operate the vacuum pump, if such a pump is employed. Among capital costs, the costs of the pump and condenser are assigned to this step, whereas other costs are assigned to the first step. Adapting the methodology described by Realff and Kawajiri (Sinha et al., 2017), the committee estimated the individual contributors to the cost of CO_2 capture for different parameter sets.

TABLE 5.8 Estimated CO_2 Emissions Generated by a Solid Sorbent Direct Air Capture System That Removes 1 Mt/y CO_2 Depending on Energy Source

		Carbon Emissions (Mt/y CO_2)	
Step	**Energy Source**	**Mid-Range (low-high, 2-4)**	**Full-Range (best-worst, 1-5)**
Desorption heat	Solar	0.008-0.01	0.004-0.04
	Nuclear	0.004-0.005	0.002-0.02
	Natural gas	0.22-0.30	0.12-1.2
	Coal	0.32-0.44	0.17-1.7
Air contactor fans	Solar	0.0004-0.008	0.0005-0.026
	Wind	0.002-0.003	0.0002-0.012
	Nuclear	0.002-0.004	0.0002-0.013
	Natural gas	0.07-0.14	0.01-0.47
	Coal	0.15-0.3	0.019-1
Vacuum pump	Solar	$(0.93\text{-}1.9) \times 10^{-6}$	$(0.0015\text{-}2.8) \times 10^{-5}$
	Wind	$(0.47\text{-}0.7) \times 10^{-6}$	$(0.0059\text{-}13) \times 10^{-6}$
	Nuclear	$(0.47\text{-}0.93) \times 10^{-6}$	$(0.0059\text{-}14) \times 10^{-6}$
	Natural Gas	$(1.6\text{-}3.3) \times 10^{-5}$	$(0.029\text{-}50) \times 10^{-5}$
	Coal	$(0.35\text{-}0.7) \times 10^{-4}$	$(0.0056\text{-}10.8) \times 10^{-4}$
Total	Solar/solar	0.0084-0.018	0.0045-0.066
	Nuclear/nuclear	0.006-0.009	0.0022-0.032
	Solar/natural gas	0.22-0.30	0.12-1.2
	Wind/natural gas	0.22-0.30	0.12-1.2
	Natural gas/natural gas	0.29-0.44	0.13-1.67
	Coal/coal	0.47-0.74	0.19-2.7

Note: Emission factors for different energy sources are referenced near the start of this chapter (NREL, 2013).

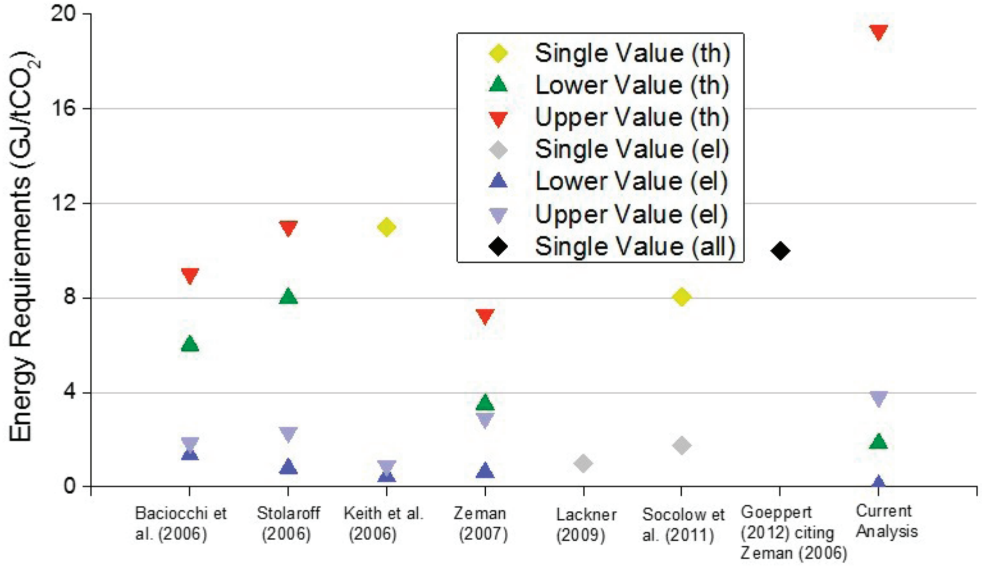

FIGURE 5.5 Literature-reported energy requirements for solid sorbent direct air capture systems and values calculated in this study. SOURCE: Adapted from Broehm et al., 2015.

For a generic solid sorbent system, with all parameters varied within the ranges listed in Table 5.5, the committee calculated carbon capture costs ranging from \$18/tCO_2 to over \$1,000/t CO_2. The combination of every best-case parameter resulted in the lower bound (1-best), a scenario that is likely unachievable due to correlations among various parameters, where optimizing one may move another away from an optimum (using currently known materials and approaches). There are many ways to design a poor process with costs that exceed \$1,000/tCO_2, with the calculated upper bound in this parameter space designated as the worst case (5-worst). As noted above, three other, more realistic scenarios were also considered (2-low, 3-mid, 4-high). A description of the approach used for the calculations is provided in Appendix D, and the specific parameter used in each case are provided in Table 5.9. A sensitivity analysis of the impact of the various parameters is provided in Table 5.10. All five scenarios are shown, making it clear that the adsorbent CAPEX dominates the overall cost. In comparison, no other capital and operating costs are substantial cost drivers. This demonstrates the importance of adsorbent cost and lifetime, as well as the potential for adsorbent material innovations to further reduce costs.

As noted above, the cost estimates span a wide range. Disregarding the lower bound as not realistically achievable and the upper bound as prohibitively expensive, the middle range of scenarios is perhaps most instructive. These estimates yielded capture costs of \$88-228/t CO_2 for a generic solid sorbent direct air capture system. It is plausible that these costs could be reached within the next decade, considering that Climeworks has reported a capture cost of about \$600/tCO_2 for its first generation commercial plant. From this point, costs should decline as process design and process operation improve, falling into the range calculated above.

This analysis of solid sorbent direct air capture systems reveals the following observations. First, processes that are not specifically optimized for direct air capture will generate costs that fall within the range estimated by House et al. (≥ \$1,000/tCO_2, 2011). Second, direct air capture processes that employ physically realistic process parameters designed for direct air capture systems can generate costs in the range of \$100-600/tCO_2. Third, large-scale processes (over 1 Mt/y CO_2) employing known materials and gas-solid contactors in the most promising scenarios could generate costs close to \$100/tCO_2, though no such large-scale, continuously operating installation exists at this time.

Summary of Analysis of Solvent and Solid Sorbent Direct Air Capture Systems

Table 5.11 presents the estimated energy required for direct air capture, along with the CO_2 footprint and net CO_2 removal assuming a plant designed to capture 1 Mt/y CO_2. Both liquid solvent and solid sorbent cases have been considered, with scenarios that vary to meet the electric and thermal needs of the direct air capture plant.

TABLE 5.9 Input Parameters Used for Cost Estimates for the Generic Solid Sorbent Direct Air Capture System, with Selected Outputs

Parameters	1-Best	2-Low	3-Mid	4-High	5-Worst
Adsorbent purchase cost (\$/kg)	15	50	50	50	100
Adsorbent life (y)	5	0.5	0.5	0.5	0.25
Sorbent total capacity (mol/kg)	1.5	1.0	1.0	1.0	0.5
Desorption swing capacity (mol/mol)	0.90	0.8	0.8	0.8	0.75
Contactor to adsorbent ratio (kg/kg)	0.1	0.1	0.2	1.0	4.0
Desorption pressure (bar)	0.2	0.5	0.5	0.5	1.0
<u>Outputs</u>					
Final desorption temperature (K)	340	360	360	360	373
Cycle time (min)	39	16	28	42	26

TABLE 5.10 Estimated Annualized Capital (CAPEX) and Operating (OPEX) Costs for a Generic Solid Sorbent Direct Air Capture System with a Capacity of 1 Mt/y CO_2 Removal

Parameters	1-Best	2-Low	3-Mid	4-High	5-Worst
Adsorbent CAPEX	3.6	70	122	186	988
Adsorption OPEX	1.3	9	12	19	4.3
Blower CAPEX	3.6	2.1	3.7	6.7	13.7
Vacuum pump CAPEX	4.5	2.6	4.7	8.5	17.4
Steam OPEX	2.5	2.2	2.4	3	43
Condenser CAPEX	0.03	0.07	0.075	0.1	0.4
Contactor CAPEX	2.2	1.3	2.3	4.1	8.4
Vacuum pump OPEX	0.3	0.2	0.2	0.24	0.3

Energy Requirements

The thermal component of the energy required to operate a direct air capture plant dominates the electric component because of the need for strong CO_2-binding chemistry. The electricity required is used to operate fans and pumps and can be minimized through the design of a shallow contactor to minimize pressure drop through the system. The strong-binding chemistry is necessary to produce high-purity CO_2 from dilute CO_2 in the air, that is, approximately 400 ppm. The thermal requirement for regeneration of the material used for capture may be satisfied by burning natural gas directly, with the generated heat used for regeneration directly or indirectly through the production of steam. Another option for meeting the thermal requirement is H_2 combustion, which results in zero CO_2 emissions. It is clear from Table 5.10 that the thermal requirement for the liquid solvent system[13] is significantly larger than that for the solid sorbent system. This is because the liquid solvent approach involves heating $CaCO_3$ up to 900°C to produce high-purity CO_2, while the temperature required for solid sorbent regeneration is much lower at approximately 100°C. The table presents a range of energy estimates for the solid sorbent–based approach.

The electric requirement is similar regardless of the approach. For the solvent-based approach, H_2 combustion was also considered, with H_2 produced through electrolysis. If using the grid mix of electricity, this approach increases that component

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[13] Solvent systems are not inherently disadvantaged compared to solid sorbent systems, and both can operate in high- or low-temperature regimes if the sorption/desorption chemistry is designed to do so.

TABLE 5.11 Summary of Estimated Energy Requirements, CO_2 Footprint, and Carbon Capture for 1 Mt/y CO_2 Liquid Solvent and Solid Sorbent Direct Air Capture Systems

Direct Air Capture System	**Energy Source**		**Energy Required (GJ/t CO_2)**		**CO_2 Generated (Mt/y CO_2)**		**Net CO_2 Avoided**	**Capture Cost (\$/t CO_2)**	
	Electric	Thermal	Electric	Thermal	Electric	Thermal	(Mt/y CO_2)	Captured	Net Removed[a]
Liquid Solvent	NG	NG	0.74-1.7	7.7-10.7	0.11-0.23	0.47-0.66	0.11-0.42	147-264	199-357
	coal	NG	0.74-1.7	7.7-10.7	0.18-0.38	0.47-0.66	0-0.35	147-264	233-419
	wind	NG	0.74-1.7	7.7-10.7	0.004-0.009	0.47-0.66	0.34-0.53	141-265	156-293
	solar	NG	0.74-1.7	7.7-10.7	0.01-0.03	0.47-0.66	0.31-0.52	145-265	165-294
	nuclear	NG	0.74-1.7	7.7-10.7	0.01-0.02	0.47-0.66	0.32-0.52	154-279	173-310
	solar	H2[b]	11.6-19.8	7.7-10.7	0.01-0.03	0	0.99	317-501	320-506
Solid Sorbent[c]	solar	solar	0.55-1.1	3.4-4.8	0.0004-0.008	0.008-0.01	0.892-0.992	88-228	89-256
	nuclear	nuclear	0.55-1.1	3.4-4.8	0.002-0.004	0.004-0.005	0.91-0.994	88-228	89-250
	solar	NG	0.55-1.1	3.4-4.8	0.0004-0.008	0.22-0.30	0.70-0.78	88-228	113-326
	wind	NG	0.55-1.1	3.4-4.8	0.002-0.003	0.22-0.30	0.70-0.78	88-228	113-326
	NG	NG	0.55-1.1	3.4-4.8	0.07-0.14	0.22-0.30	0.56-0.71	88-228	124-407
	coal	coal	0.55-1.1	3.4-4.8	0.15-0.3	0.32-0.44	0.26-0.53	88-228	166-877

[a] Assuming the use of an oxy-fired kiln to provide heat from natural gas in the calcination process, leading to greater CO_2 production and hence lower cost of net CO_2 removal, using a basis of 1.3 Mt CO_2 for NG/NG, 1.2 Mt CO_2 for coal/NG. (NG = natural gas).

[b] Assuming all hydrogen is produced via electrolysis using near zero-carbon power.

[c] Scenarios range from 2-low to 4-high.

significantly; however, the electricity could be sourced from carbon-free nuclear, wind, or solar, which would maximize the impact of this pathway to direct air capture.

Carbon Footprint

If the electricity or thermal energy requirements are met using fossil fuels, then significant CO_2 emissions will result, thereby reducing the effect of a direct air capture plant in terms of CO_2 removal from the air. The committee assumed a grid mix, carbon-free paths such as nuclear, wind, and solar thermal, and fossil-intensive paths such as coal and natural gas. The CO_2 emitted from meeting the energy requirements increases as expected—from nuclear, wind, or solar thermal, to natural gas, and finally to coal as the source with the greatest CO_2 emissions. Because the solvent-based approach regenerates $CaCO_3$ in an oxy-fired kiln, it can easily capture the CO_2 generated from burning natural gas to meet the thermal requirements in addition to maximizing the removal of CO_2 from the air (Keith et al., 2018). In fact, on average, an additional 0.5 Mt/y CO is produced and captured along with the CO_2 from air by condensing the exhaust mixture of CO_2 and water vapor. In principle, any process can employ fossil energy with carbon capture from the energy emissions to reduce its carbon footprint, although at additional capital and operating costs. Such a scenario was considered here for the solvent case because it is an inherent part of the Carbon Engineering design.

Carbon Removal Cost

If fossil-based energy resources are used to provide the energy requirements of a direct air capture system, then an accurate estimate of the cost to removing CO_2 from the air requires consideration of the *net* CO_2 *removed* because burning fossil fuels produces CO_2. On average, the costs for *net* CO_2 *removed* for the solid sorbent–based approach range from \$89 to \$877/tCO_2, depending on the adsorption scenario, while the costs range for the solvent-based approach range from \$156 to \$506/tCO_2, depending on the use of natural gas or renewable H_2 for the thermal source.

IMPACT POTENTIAL

The potential for direct air capture flux and capacity has no fundamental physical limit, making its primary limitation financial. The potential impact is limited by the investment required to scale direct air capture as well as the availability of geologic storage to sequester the captured CO_2. Available pore space must be shared with the CO_2 produced from conventional carbon capture efforts in addition to BECCS. The mainstream literature has often stated that an advantage of a direct air capture plant is that "it can be placed anywhere." Although direct air capture can be deployed in many locations where BECCS cannot—because it does not require arable land and therefore may have greater access to remote pore volumes—this assessment should be approached with caution. Deployment of direct air capture on any significant scale (i.e., thousands of tons CO_2 removed per year) requires significant infrastructure, energy, and land. At 1 Gt/y CO_2 removal and \$100/t CO_2 for combined separation, transport, and reliable sequestration, the total investment would be about \$100 billion per year or 0.5 percent of U.S. gross domestic product (GDP). At a global scale of 5 Gt/y CO_2 removal and \$100/t CO_2, the total investment increases to about \$500 billion or 0.6 percent of global GDP. Achieving this rate and scale of CO_2 removal will require substantial investments in fundamental research, demonstration, and deployment.

To maximize the net emissions removed from the air and the ultimate impact of direct air capture and sequestration, the use of renewable energy resources should be maximized where possible. The integration of renewable energy with base load natural gas, or use of combined heat and power units, could be a cost-effective approach to scaling up direct air capture and sequestration.

SECONDARY IMPACTS

Land

Direct air capture systems have significantly fewer land requirements than do afforestation/reforestation and BECCS approaches, and because they do not require arable land their impacts on biodiversity would be much smaller. Consider the Amazon rainforest as an example. The net primary production of the Amazon is approximately 270 km^2 per Mt/y CO_2. With a land area of 5.5 million km^2, this equates to an annual CO_2 removal of about 20 Gt CO_2. As discussed later in this section, the land area requirement for the equivalent CO_2 removal using direct air capture is roughly 40 times smaller at 7 km^2 per Mt CO_2 if powered by natural gas. If you consider a temperate deciduous forest with a net primary production of 390 km^2 per Mt/y CO_2 and an average tree density of 200 per acre, a single tree acts to remove (net), on average, 50 kg CO_2/y; in this sense, a 1 Mt CO_2 direct air capture system does the work of 20 million tree equivalents, or a forest spanning 100,000 acres.

In general, the land that is required for direct air capture is impacted by the size of the contactor and the spacing requirements of multiple contactors and contactor configuration. The land area estimates discussed in this section are those required to capture 1 Mt/y CO_2 at 65-75 percent capture.

Liquid Solvent Systems: In the contactor design of Keith and Holmes, the cross-sectional inlet area is oriented normal to the land surface. This use of vertical space minimizes direct land use per contactor structure. For example, a 4,000 m^2 inlet area is achieved through a structure containing packing dimensions of 20 m high by 200 m long by 8 m wide. These packing dimensions are a result of a full structural engineering analysis and cost optimization that examined sensitivity to height and width (Holmes and Keith, 2012). If the packing material is housed in a shell structure that is 110 percent of the packing dimensions, then the direct land use is roughly 2,000 m^2 per contactor, or half the inlet cross-sectional area. At 400 ppm CO_2 in air and 100 percent capture efficiency, the capture of 1 t/y CO_2 from air corresponds to an air volumetric flow rate = 4.09×10^{-2} m^3/s. Assuming an air inlet velocity = 1.5 m/s and CO_2 capture efficiency = 75 percent, an air contactor cross-sectional area = 38,000 m^2 is obtained from:

$$A_{inlet} = \frac{\dot{V}_{air}}{v_{air} \cdot \delta_{CO2}}$$

At the optimized conditions considered in this study (75 percent capture and V = 1.5 m/s), a cross-sectional area of roughly 38,000 m^2 is required to capture 1 Mt/y CO_2 or the equivalent of 10 air contactor units with packing dimension of 20 m × 200 m × 8 m per unit.

The array of multiple contactors needs to be arranged around a centralized regeneration facility and should be positioned to minimize piping and other associated infrastructure costs. An important consideration in contactor arrangement involves the region where CO_2-depleted air exits the contactor. To maximize separation efficiency, this region should not feed into the intake of an adjacent contactor. Rather, appropriate spacing is required for proper tropospheric mixing to occur such that air entering an adjacent contactor has fully equilibrated to ambient conditions (400 ppm CO_2) (Figure 5.6). A centralized regeneration facility including the causticizer, slaker, calciner, air separation unit, and other auxiliary equipment is expected to have a direct land impact of approximately 20 percent that of the air contactor array (Keith et al., 2018). When multiple contactors are positioned to minimize piping and other infrastructure costs, the direct land required is approximately 24,000 m^2 (~6 acres) including the regeneration facility (Keith et al., 2018). Indirect land use accounts for the spacing between contactors if multiple direct air capture plants are to be constructed in a single area. In a single-plant design, although there would be no adjacent plant, the region of tropospheric mixing may pose risks not yet well understood because of the lower local concentration of CO_2. For example, plants of the C3 photosynthetic genotype (80-95 percent of all species) grown under glacial conditions ($CO_2 < 200$ ppm) are known to suffer from compromised survival and limited reproduction. Further, these conditions may affect plant tolerance to drought, heat, and other stressors, an important consideration if direct air capture siting includes arable land (Sage and Cowling, 1999; Ward, 2005). To avoid unwanted consequences or potential trophic cascades related to this CO_2-depleted region, this land area is assigned as indirect land use regardless of a single or multiple plant design. When indirect land use is considered, the total land requirement jumps by about 300 times to 7 km^2 (~1,730 acres).

The land area discussed does not consider an onsite power island. The average size of a natural gas plant in the United States is 30 acres, or 1,400 m^2/MW (Stevens et al., 2017). Indirect land use associated with resource production, but excluding transmission and transportation, increases the land requirement to approximately 8100 m^2/MW, or 2.4 km^2 for a power requirement of 300 MW. Additional land may be required if onsite renewable energy (e.g., PV solar panels or concentrated solar thermal) is used to offset any portion of the electric and thermal requirements. The National Renewable Energy Laboratory reports a generation-weighted[14] total land use of 3.0 acres GWh^{-1} yr^{-1} for concentrated solar thermal, and 5.5 acres GWh^{-1} yr^{-1} for small two-axis flat panel PV power plants (Ong et al., 2013). If solar is used to offset 25 percent of the electric and thermal requirements, an additional 3,600 acres of total land area is required. In the theoretical limit where solar power and the Conservation Stewardship Program (CSP) are used to offset all electric and thermal requirements, total land use escalates to 14,500 acres, or roughly 58.6 km^2. One-hundred such facilities (representing 100 Mt CO_2 removal per year) would require a land area roughly the size of Delaware.

The National Renewable Energy Laboratory also reports land-use data for wind generation. Here, because of the wide range of wind configurations and absence of a universally accepted metric for land use in wind plants, the average total land area is 40±25 acres GWh^{-1} yr^{-1}. Although this requirement is larger than for solar, a key advantage of wind power is the ability to use the land between turbines, because the turbine footprint is less than 10 percent of the directly impacted land area. Direct land

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[14] Total land area requirements vary due to location, array configuration, derate factor, and tracking technology, and range from 2 to 7 acres/GWh/y for small two-axis PV, and from 2 to 8 acres/GWh/y for concentrated solar power.

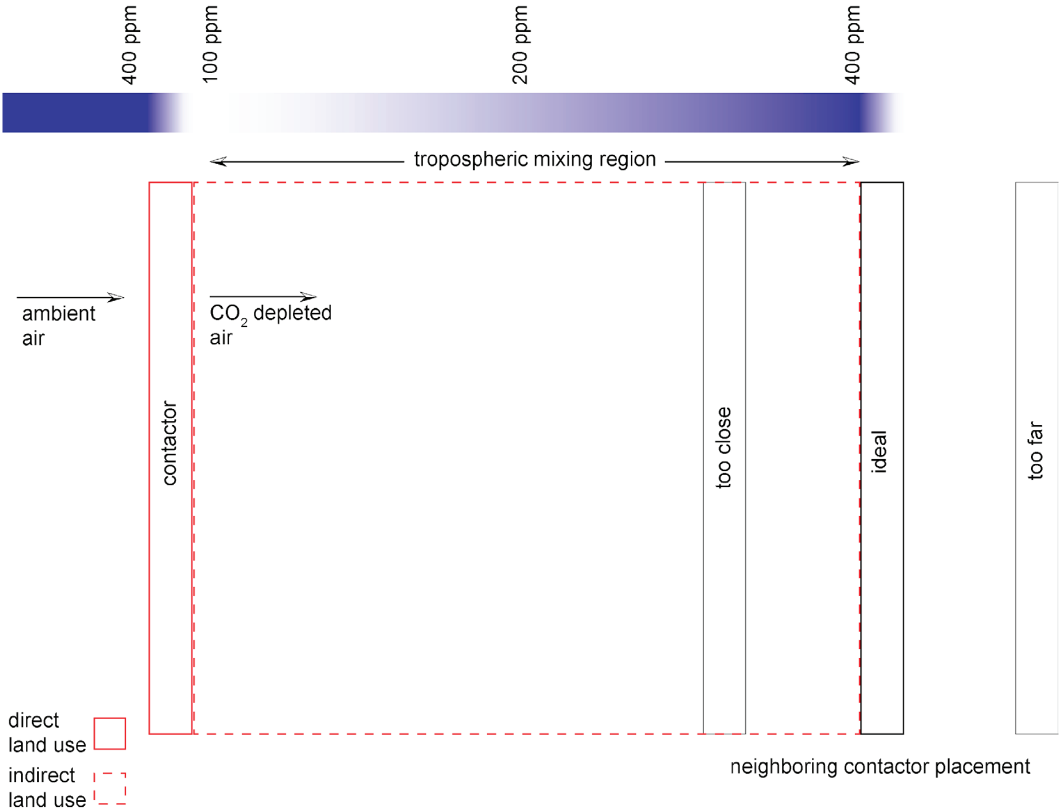

FIGURE 5.6 Direct and indirect land use for a direct air capture system air contactor configuration. NOTE: When positioning adjacent contactors, care should be taken to allow the outgas of one contactor to fully equilibrate to ambient conditions before entering the next contactor.

use may be avoided altogether through contracts with off-shore wind farms, which typically experience higher capacity factors than their land-based counterparts.

An alternative configuration for sorbent-based direct air capture involves onsite electrolysis of H_2 using solar power. The electric demand here ranges from 400 to 500+ MW for a 1 $MtCO_2$ removal plant. Using the generation-weighted average land intensity for solar-PV power production quoted above, the land footprint for this configuration is 19,250-25,500 acres, or roughly 80 to 100 km^2.

An important consideration in these land area calculations pertains to the inter-contactor spacing depicted in Figure 5.6. The direct land use of a configuration, including the contactor array and regeneration equipment, but excluding land for power, is 0.3 percent of the total land footprint. Thus, a direct air capture operator might decide to use the indirect land space to house—in part—on-site power infrastructure, assuming the presence of such equipment has a negligible impact on the equilibration of contactor outgas to ambient levels (400 ppm). For example, this space may be suitable for the installation of low-lying solar panels, whereas wind turbines could potentially reduce wind speed, which would impact the rate of tropospheric air mixing and potentially the velocity of air entering an adjacent contactor. For optimal land use, the impact of different land uses on overall direct air capture plant performance must be well understood.

Solid Sorbent Systems: Similar contactor spacing constraints exist as discussed above for the solvent case. Today, companies developing commercial direct air capture technologies are targeting designs that remove CO_2 from the air at areal intensities of ~2-200 kt/y-acre CO_2 depending on the technology. This footprint accounts for the land area for process equipment, areal mixing, and safety margins, with the air/solid contacting equipment covering only a small fraction of the total plant area, typically less than 5 percent. For the hypothetical adsorption direct air capture process considered above, a single direct air capture plant would capture ~200-1,370 kg CO_2/m^2-y.[15] To capture 1 Mt/y CO_2, given the capture rates mentioned above, numerous such units would typically be deployed (i.e., scaling out, rather than scaling up). Given the range of capture rates, 200-1,250 acres of land are required for 1 Mt/y CO_2, with the middle three scenarios (2-low to 4-high) requiring 300-425 acres. These areal requirements consider only the direct air capture plant. To also account for local power generation, the land requirements increase to 550-800 acres for natural gas–based thermal and electrical energy, or 1,355-,2450 acres for natural gas–based thermal energy and solar–based electrical energy, assuming no space in the direct air capture plant footprint can accommodate power generation equipment.

Water

Water loss in direct air capture primarily occurs during the sorbent-air contacting process. In both the proposed solid and solution-based direct air capture processes, most water use is contained in closed-loop systems, whereby water is continuously recycled. Nonetheless, nearly all processes have the potential for water loss, and this parameter should be carefully considered when any new process is developed.

Liquid Solvent Systems: Water loss in the contactor is mainly due to evaporation, with a trivial contribution from drift loss. As outlined in the Section on Energetics and

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[15] This is the range spanned by the five scenarios, from 1-best to 5-worst.

Carbon Footprint, 8.2 Mt of make-up water should be supplemented to offset this loss each year. This value is calculated at 65 percent humidity, 16, 2M KOH(aq) solution and may increase if the direct air capture plant is placed in more arid conditions. Stolaroff et al. (2008) show that if the relative humidity is reduced to 50 percent, the evaporative water loss increases from 20 mol H_2O/mol CO_2 to 80 mol H_2O/mol CO_2, a four-fold increase. Higher molarity solutions have a lower vapor pressure and experience lower evaporative losses. The direct air capture operator may choose to mitigate water loss through the adjustment of solvent molarity based on ambient conditions. "Drift" loss is a phenomenon described by the cooling industry as the escape of droplets from the contactor as a result of the cross-flow configuration. Keith et al. (2018) describe measurements that indicate that airborne KOH concentrations less than 0.6 mg/m^3 air flow out of the contactor, which is below the National Institute for Occupational Safety and Health upper exposure limit of 2.0 mg/m^3. Demonstration-scale projects should conduct further measurements of this kind to minimize the risk associated with the configuration choice.

Cooling water is required to condense out water vapor from the calcination flue gas. At a flue gas output of roughly 640 ft^3/min, roughly 1,300L/ min of water is required. This water is largely recirculated and does not contribute significantly to the overall water consumption.

In the oxy-firing process, combustion water and CO_2 are produced through natural gas combustion in an oxygen-enriched environment. According to Keith et al. (2018), a water "knock-out" stage occurs before CO_2 compression. This water is combined with a make-up feed of 531 t/h in a settling tank, to be subsequently mixed with CaO to produced calcium hydroxide for the contactor.

The majority of process waste consists of Ca-based solids that precipitate out of the sorbent cycle because of contaminants that enter via the contactor. The generic solvent process does not produce a significant amount of wastewater, and onsite wastewater treatment is not anticipated.

Solid Sorbent Systems: Direct air capture companies currently employ processes that vary widely in terms of freshwater usage. The hypothetical adsorption-based direct air capture process analyzed here, which relies on T/VSA using saturated steam condensation on the adsorbent and contactor as the mode of heat transfer, can result in water loss to the environment. For those who employ this approach, such as Global Thermostat, the potential water loss is usually accepted as a consequence of the improved heat transfer and overall process performance offered by this mode of heat transfer. In an alternate approach, sorbent regeneration can be accomplished by indirect heat transfer such that steam is contained in a fully closed system, allowing for negligible water losses in some cases. It has been reported that under some operating conditions, solid sorbent–based processes produce fresh water, which is harvested from the air concurrently with the CO_2 capture.

In a typical configuration of the hypothetical adsorption-based direct air capture process, water loss would amount to ~1.6 MtH_2O/y for capture of 1 Mt/y CO_2 (about 4 moles of water lost per moles of CO_2 captured). This value could vary significantly depending on the ambient humidity at the capture site, and as noted above, in some scenarios fresh water can actually be produced. Water loss would be expected to be larger in drier climates and smaller in humid climates. In addition, water is required for the synthesis of the solid sorbents, and considering the short sorbent lifetimes, water consumption for this purpose could be substantial.

At least one company, Infinitree, is developing a solid sorbent–based technology that deploys an entirely different capture approach. Rather than a T/VSA process and solid amine-based adsorbents, this technology would deploy quaternary ammonium-based sorbents that use a swing in humidity to induce CO_2 adsorption and desorption. With this approach, which differs substantially from the hypothetical process outlined in this chapter, CO_2 is captured under dry conditions and then desorbed and concentrated under humid conditions.

In the academic literature, water loss from hypothetical direct air capture processes has thus far received marginal attention relative to other factors such as energy use. Future R&D efforts should carefully consider water production/use.

Environmental

One potential environmental impact of direct air capture processes is the depletion of CO_2 from the air exiting the contactor. Many studies have examined the environmental impact of elevated atmospheric CO_2, but few studies have examined the impact of lowered CO_2 levels. De Marchin et al. demonstrated that reduced CO_2 leads to lower photosystem II (PSII) photochemical efficiency in algae cultures (de Marchin et al., 2015). This region of local CO_2 depletion could have adverse effects on crop efficiency and the overall health of local habitats. Thus, direct air capture siting should consider the nature and role of regions directly "downwind" of large CO_2-scrubbing contactors.

Liquid Solvent Systems: The generic solvent-based direct air capture process involves two chemical-intensive processes: (1) contact of ambient CO_2 in a caustic KOH(aq) solution and (2) regeneration of KOH through a Ca-based causticization and chemical swing cycle. Both of these processes are mature, well studied, and long employed in industry: KOH(aq) is used to scrub CO_2 as a pre-stage in cryogenic air separation (Holmes and Keith, 2012), and the Ca-based recovery cycle is based on the Kraft process used by the pulp and paper industry (Baciocchi et al., 2006). Wastewater is not generated in significant amounts in this process, and solid waste buildup in the recovery cycle should have similar environmental implications and disposal guidelines as the reclaimer waste in a traditional monoethanolamine (MEA)-scrubbing operation.

Solid Sorbent Systems: For the generic adsorption-based direct air capture process, chemicals are primarily released from the active CO_2 adsorbing materials, which are intermittently exposed to the ambient air. Most existing companies employ amine-based solid adsorbents, which are not indefinitely stable under aerobic conditions. Studies of volatile organic carbon emissions from conventional carbon capture plants employing liquid amine solutions as capture agents suggest that amine-based sorbents can break down over time into species, such as ammonia, nitrosamines, and other nitrogen-containing compounds, that may damage organisms or the environment (Azzi et al., 2014; de Koeijer et al., 2013; Karl et al., 2011, 2014; Ravnum et al., 2014; Zhang et al., 2014). Little is known about emissions from solid amine-based adsorbents, which is an area where research could clarify the potential emissions.

RESEARCH AGENDA

At this time, it is not possible to select either solid sorbent or liquid solvent as a leading technology. Concerted R&D on both approaches is needed, with the understanding that scalability, cost, and suitability for different locations will vary.

However, gaps in basic science and engineering knowledge do not appear to be limiting the deployment of direct air capture processes. Direct air capture solves only part of the problem because it only captures CO_2; it does not on its own sequester the captured gas. Rather, the absence of a natural economic driver, such as a cost on carbon, limits the rapid testing and deployment of direct air capture. Consequently, slow deployment limits the amount of publicly available data for techno-economic analyses of the various known approaches to direct air capture. This in turn limits the ability of policymakers to understand the costs to deploy direct air capture to achieve the scale of negative emissions needed to comply with the Paris agreement. As such, the most significant research will bolster public support for an array of pilot-scale studies of integrated direct air capture processes that can be operated for extended time periods to assess process performance and reliability, and will provide the data necessary to improve and refine process techno-economic models.

Nonetheless, advances in basic science and engineering can continue to reduce the costs of direct air capture. In the section below, the committee lays out a research agenda for direct air capture to contribute to the removal of CO_2 from the atmosphere, including the associated costs and options for implementation (Table 5.12).

Basic Research

Although basic science innovations are not be the primary barrier for initial deployment of direct air capture technologies, they are important to expanding the scope of approaches to direct air capture, providing new opportunities for technology breakthroughs that will drive down costs. For example, advanced process designs (e.g., shallow contactor to minimize pressure drop, improved packing material properties and contactor designs) may be developed for liquid-solvent air capture. In addition, improvements in the material properties of solvents and sorbents could drive down costs. For example, the two key parameters that impact the capital design of the separation process for solvent-based direct air capture are kinetics of reaction and solvent capacity. The overall kinetics of CO_2 capture are impacted by the diffusion kinetics, that is, the time it takes for CO_2 to diffuse from the air to the chemical binding agent. In a similar manner, the diffusion of CO_2 out of the material is important in terms of producing high-purity CO_2. A slower reaction, slower diffusion, and a lower capacity lead to the need for more material to capture a given amount of CO_2. In turn, the number of units required for capture increases, driving up the capital cost for the overall system. Hence, increasing kinetics and capacity (e.g., through catalysis using novel solvents) will lower the solvent requirement and therefore capital costs. The committee recommends an investment in basic research and early-phase technology development of $30M/y for 10 years. This investment would cover approximately 30 projects per year in several areas, each with an approximate budget of $1M/y for 3 years.

Examples of basic science innovations that could significantly advance direct air capture technologies include:

(i) Low-cost solid sorbents, ideally costing <$50/kg, that are designed in conjunction with a suitable gas/solid contactor capable of deployment at scale. Solid sorbents are typically developed in physically unrealistic (for direct air capture) contactors, such as fixed beds, and often the sorbents are made from prohibitively expensive materials. Low cost, scalable sorbents developed in conjunction with appropriate contactors, enabled by scientists and process engineers working together at the earliest stages of development, will facilitate more rapid development of practical, scalable direct air capture processes.

TABLE 5.12 Recommended Direct Air Capture Research Agenda: Tasks, Budget, Duration, and Justification

Phase	Tasks	Annual Budget ($M)	Duration (years)	Justification
Basic Science and Applied Research	• Simulate, synthesize, test new materials (solvent/sorbents) • Design, model, test novel equipment concepts • Design and model novel system concepts, some specifically targeting renewable integration	20-30	10	Project Cost: ~ $1M Project Duration: ~3 y Project Number: 20-30/y Project Staff: ~ 1 FTE
	Establish independent evaluation for • materials performance testing, characterization, validation • public materials database creation and management	3-5	10	Contracts: 2 Contract Staff: 3-5 FTE
Development	• Scale materials synthesis to > 100 kg scale • Design and test novel equipment for pilot scale • Test system innovations on integrated lab-scale direct air capture system (> 100 kg/d CO_2)	10-15	10	Project Cost: ~ $5M Project Duration: 3 y Project Number: 2-3/y Project Staff: ~ 3 FTE
	Establish third-party evaluation for material synthesis economic analyses • bulk materials performance testing, characterization, and validation • equipment testing, characterization, and validation • basic engineering design package • creation and management of public database of materials and equipment • stage-gate for demonstration-scale pilot plants	3-10	10	Contracts: 2-5 Contract Staff: 3-5 FTE Fully Loaded FTE: $500k

continued

TABLE 5.12 Continued

Phase	Tasks	Annual Budget ($M)	Duration (years)	Justification
Demonstration	• Design, build, and test pilot-scale direct air capture systems (> 1000 t/y CO_2)	20-40	10	Project Cost: ~ $20M Project Duration: 3 y Project Number: 1-2/y average Project Staff: 10-15 FTE Nominally, 3-5 projects in years 1-3, 5-10 projects in years 4-6, and 3-5 projects in years 8-10
	Establish national direct air capture test center to • support pilot plant demonstration projects • develop third-party front-end engineering design and economic analysis • maintain public record of pilot plant performance	10-20	10	Contracts: 1 Contract Staff: 20-30 FTE Fully Loaded FTE: $500K

TABLE 5.12 Continued

Phase	Tasks	Annual Budget ($M)	Duration (years)	Justification
Deployment	• Scale up/out siting factors to optimize direct air capture performance (>10,000 t/y)	100	10	Project Cost: $100M Project Duration: 3-5 y Project Number: 1/y Project Staff: 60-70 FTE Project Number: 1 every 2 years First projects after 3-year pilot projects (1,000 t/y CO_2) depending on success of technologies from funding above, if success above justified such large investment
	Engage National Direct Air Capture Test Center to • support full-scale plant demonstration projects • maintain public record of full-scale plant performance and economics	15-20	10	Contract: 1 Contract Staff: 30-40 FTE Fully Loaded FTE: $500k

(ii) Strategies that minimize the large thermal requirements of direct air capture processes, which will be crucial to reducing the operating costs of these systems. Examples include, but are not limited to, lean solvents (+/- catalysts) as well as gas/solid contactors that limit the mass of material not directly involved in binding CO_2, thereby minimizing the sensible heat load. Also important are CO_2-selective yet less strongly binding materials for CO_2 capture that lead to reduced regeneration energy.

(iii) New materials with enhanced CO_2 sorption capacity and reaction and diffusion kinetics, especially those that bind CO_2 sufficiently strongly to remove it from air under ambient conditions and that use new binding pathways or mechanisms. Simulation and modeling could be coupled to experiments to assist in the optimal design of new materials. Such materials should be characterized not only in regard to their uptake capacity, but also their uptake kinetics and cyclic stability under varied humidity conditions in a practical gas/solid contactor. Materials should offer swing capacities and reaction kinetics that are competitive with or exceed the state-of-the-art.

(iv) Advances in solvent, solid sorbent or contactor design that lead to an increase in the mass-transfer coefficient or assist in reducing the capital costs of the system
   a) liquid solvents: advanced packing materials (plastics vs metals) and optimization of solvent properties (density, surface tension, and viscosity) to maximize packing coating
   b) solid sorbents: advantageously controlling water sorption, optimally designing the sorbent pore size distribution, maximizing swing capacity, increasing sorbent durability and lifetime

(v) Identification of potential degradation products released into the environment by solvents and solid sorbents, especially from solid amine-based adsorbents that are being widely considered for deployment.

(vi) New processes that are tailored to the unique constraints of direct air capture, for example, high gas throughput and low pressure drop.

(vii) Life-cycle analyses of known and new direct air capture processes, specifically with regard to CO_2 emissions from sorbent production and use (given the sensitivity of the solid sorbent-based processes to sorbent lifetime) as well as water use.

As noted above, improvements in CO_2 solvents and sorbents are needed to reduce direct air capture system costs. However, accurate and repeatable sorption measurements under controlled conditions can be difficult to perform (e.g., simultaneous CO_2 and H_2O uptake measurements are sought), sometimes leading to conflicting results in the literature. Thus, the committee recommends that independent material performance characterization (e.g., gas/vapor sorption, Gibbs energy of formation, heat capacity, thermal conductivity, thermal expansion, thermochemical stability) using standardized testing methodologies be an integral part of the research agenda.

In addition, cost estimates for preliminary material synthesis should be independently evaluated. Materials performance data should be regularly compiled and made publicly available. Suitable institutions for independent evaluations could be a U.S. Department of Energy National Laboratory, the Department of Commerce National Institute of Standards and Technology (NIST), a nonprofit research organization, or even a manufacturer of sorption equipment. Preferably, more than one vendor would be used to ensure quality and reproducibility of measurements. An exemplary institution that performs an analogous service for solar cell research is the National Center for Photovoltaics (NCPV) at the National Renewable Energy Laboratory (NREL), where the standards for solar cell efficiency measurements have been established, providing annual publication of the best research-cell efficiencies.

Development

Materials

New materials synthesis can be expensive at the early stages, with many novel materials produced at the gram-scale. Scale-up to even kilogram-scale can often be cost prohibitive without some innovations in materials synthesis. Therefore, the committee recommends that some research funding be provided for materials synthesis scale-up, where research should aim to develop cost-effective methods for synthesizing more than 100 kg of material. To support these efforts, the committee also recommends the set-aside of funding to engage third-party vendors in performing detailed cost analyses for the synthesis of new materials of interest. Furthermore, to support materials development, the committee recommends establishment of a national center for testing bulk materials using standardized hardware to compare performance on an even basis (see above section). This center should also maintain a database of materials tested and their performance results. Unlike the independent testing of new materials under the basic research section, this center should focus on bulk materials testing (> 100 kg) that includes real-world challenges (e.g., contaminants, attrition, cycle life).

Components

System components and equipment designs (e.g., heat exchangers, contactors, regenerators, monoliths, compressors, pumps) with novel aspects that achieve more effective mass and thermal transport and/or integrated unit operations (process intensification) are of interest to reduce overall direct air capture system costs. Development funding to fabricate and test component hardware at pilot scale (> 1,000 t/y CO_2) is needed. To supplement this work, a vendor should be identified to conduct standardized, third-party equipment testing and validation. Private-sector vendors with industrial gas handling experience would be preferable to research institutions.

Systems

Development (i.e., design, construction, testing) of integrated bench-scale systems (> 100 kg/d) that assimilate low-carbon energy sources in new and cost-effective ways should be supported. Because of the large thermal requirements for regeneration of solvents and solid sorbents by temperature swing, strategies that minimize the emissions from fossil energy use for heating are needed. These include utilizing waste heat from other processes, electricity that would otherwise be shed by generators and grid operators during periods of low demand, and low-carbon energy sources. This work is important because most direct air capture processes considered to date are estimated to have significant carbon footprints if powered by unabated natural gas. The strategies noted above to reduce carbon footprint are not mutually exclusive. For example, because the quality of thermal energy required differs for each direct air capture process, ranging from low-temperature, low-value heat (70-130°C) to high-temperature, high-value heat (700-900°C), strategies to provide thermal energy for direct air capture processes from low-carbon sources (e.g., concentrated solar, geothermal, bio-energy, nuclear) for a wide operating range are needed. Similarly, all direct air capture processes considered to date require electricity. Therefore, strategies to power direct air capture processes with low-carbon electricity, potentially coupled with electrical storage that enable use of off-peak or curtailed electric power, are needed.

An additional driver to improving system design is the need for a low pressure drop in the contactor to minimize the electricity requirement. In the case of the solvent-based approach, 20 percent of the capital costs and 30 percent of the operating and maintenance costs of the entire direct air capture plant are associated with the air contactor. Figure 5.7 shows the relationship between packing depth and total estimated cost of the air contactor of a solvent-based direct air capture plant. The total estimated cost is the sum of operating and capital costs associated with the contactor. The operating costs are based on the costs of electricity for fans or blowers, while the capital costs are directly related to the material for both the infrastructure and the solvent or sorbent materials. As described above, the typical design of the air contactor is based on the need for large surface area to maximize the air contacted and subsequent CO_2 captured, while being shallow enough to minimize pressure drop and the subsequent expense of fan power to process the large amounts of air required. For example, typical contactor depths range from 6 to 8 m for direct air capture, whereas the Petra Nova absorption contactor ("tower") for post-combustion capture is nearly 15 time deeper at 115 m. The deeper the packing depth, however, the greater the amount of CO_2 captured. Hence, optimization occurs when contactor depth is maximized and fan power is minimized. To compensate for the shallow bed depth, the direct air capture contactor must have a large surface area to be able to capture the equivalent CO_2. Figure 5.7 shows that the total cost of the direct air capture air contactor decreases with increasing packing depth to a critical depth of about 8 m, after which the costs begin to increase as the fan power plays a more dominant role in the total cost. As the cost of electricity decreases, as expected, this relationship also decreases.

This highlights the opportunity that may be gained by coupling direct air capture with low-carbon energy. If, for example, wind or solar was available at the optimal price point, then the contactor could be made deeper (with subsequent smaller surface area), which could reduce the capital investment for the direct air capture plant.

Figure 5.8 shows the relationship between the electricity cost and annualized capital ($M/y) and packing depth. As can be seen, after a depth of approximately 8 m, the electricity cost begins to dominate the total cost of the air contactor. Therefore, to minimize the cost of the air contactor, it must have a shallow design, thereby leading to a significantly large surface area to capture a sufficient amount of CO_2.

To support the development of these systems, professional engineering design firms should be engaged to work with researchers to develop basic engineering design packages for novel systems, including: mass and energy balances, process flowsheets, preliminary piping and instrument diagrams, main equipment definitions and sizing, preliminary bill of materials, risk assessment, and process economics analysis. These engineering assessments will serve as a stage-gate, before which any demonstration-scale pilot projects are funded. Only projects with the potential to sequester CO_2 at a cost of less than $300/t should be considered for pilot demonstrations.

Additional systems-level areas of research may include the use of modeling and simulation to create better integrated designs, assessment of opportunities to use existing hardware and infrastructure (e.g., HVAC systems in buildings or combined heat and power systems) for direct air capture optimization and cost reduction, integration with

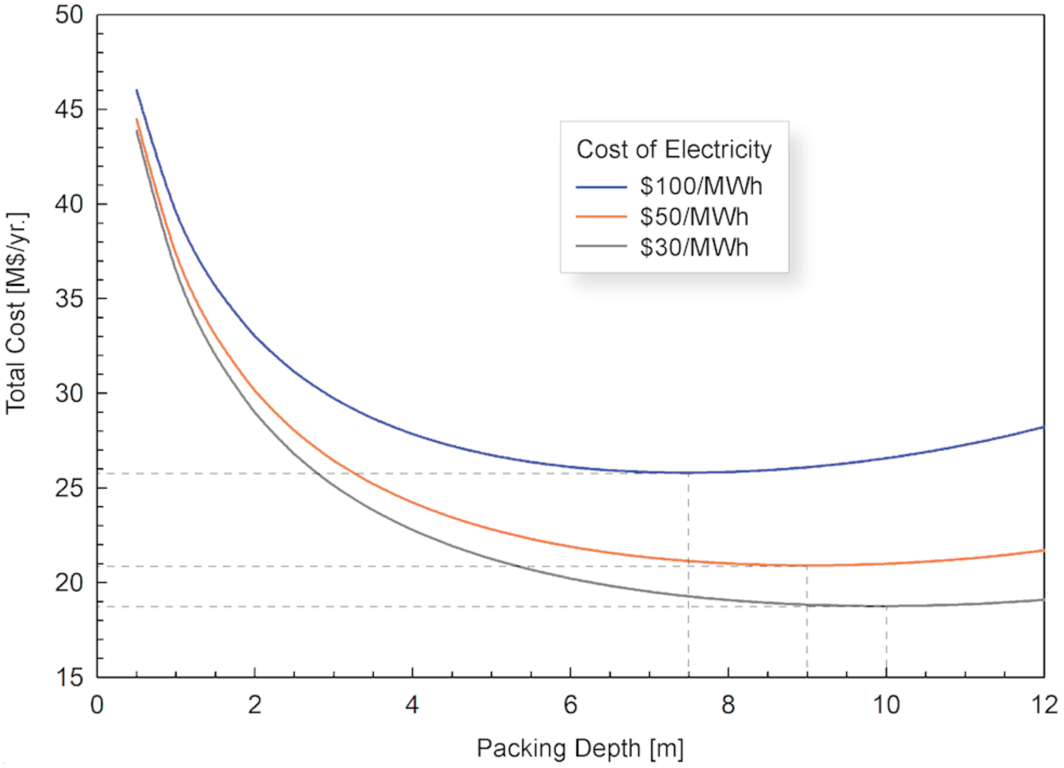

FIGURE 5.7 Relationship between packing depth and total cost of a direct air capture plant assuming costs of electricity of $30, $50, and $100/MWh.

industrial systems (e.g., steel and cement making) that have large quantities of low- to high-quality waste heat available, fabrication of contactors with ultra-low capital materials (e.g., plastics), and system modeling to assess the viability of using direct air capture as a dedicated load option to solve congestion or curtailment issues in local or regional grids.

Demonstration

The most significant barrier to the assessment and deployment of direct air capture processes is the absence of process-scale operational data to perform accurate techno-economic analyses. Currently there is no incentive for privately funded demonstration projects to provide such data.

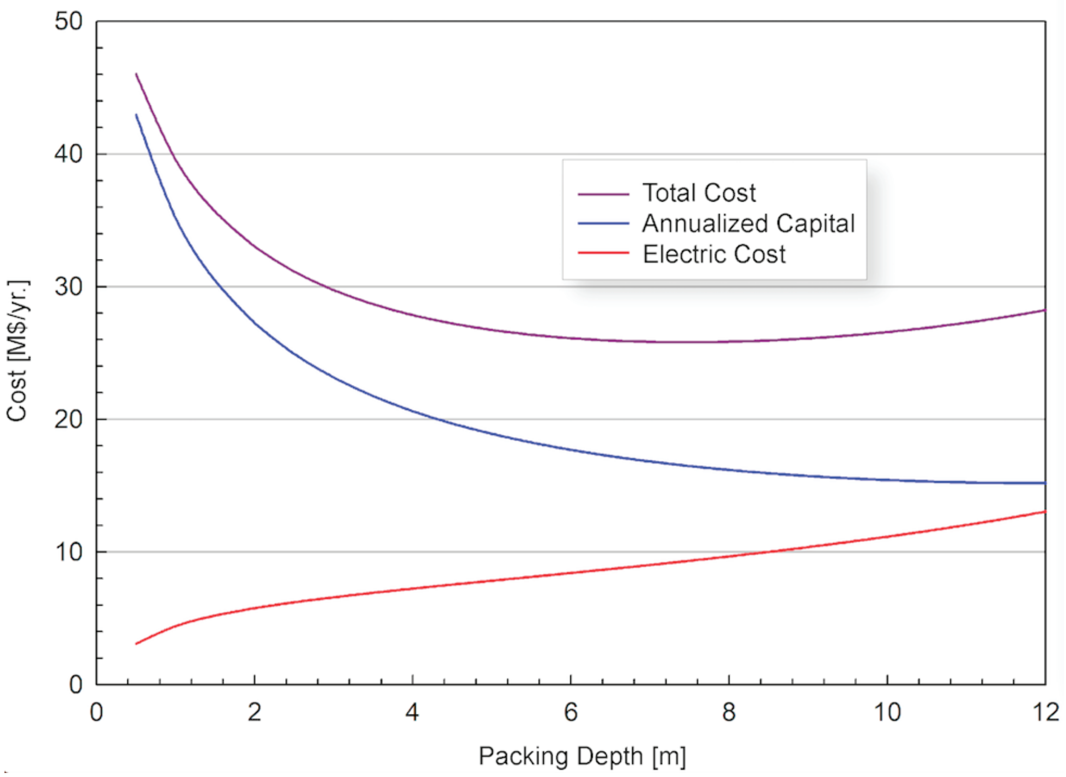

FIGURE 5.8 Relationship between the electricity, capital, and total cost and the air contactor packing depth.

Today, essentially all process-scale operations have been conducted in private companies, which may not have an interest in disclosing operational data. Furthermore, in the absence of a globally accepted cost of carbon, there is little demand for processes designed for direct air capture and sequestration. To this end, the few commercial entities that exist are generally not practicing carbon removal because the CO_2 obtained by direct air capture is sold for productive use, for example in greenhouses or the food and beverage industry. Although these opportunities are good for the budding array of commercial entities that are developing direct air capture technologies, they offer limited growth opportunities for the industry overall.

An array of publicly funded demonstration-scale studies of integrated direct air capture processes that can be operated for extended time periods is needed to generate data on process performance and reliability and to improve and refine process techno-economic models. The committee recommends a program that supports three pilot-scale projects per at year at \$20M each. Such projects should capture 1,000 t/y CO_2 per project.

Such pilot-scale studies could assess the performance of solid sorbent–based processes, for example. As noted previously, the overall process cost is most sensitive to the capital cost of the solid sorbent, which is largely dictated by the price and operation lifetime of the sorbent. To date, most studies of sorbent stability have come from academia; essentially no data have released by commercial entities. Furthermore, most academic studies test under controlled, idealized laboratory conditions for limited time periods, and the results often cannot be easily extrapolated to larger scale operation. To this end, publicly funded pilot-scale studies that provide long-term data from field operations are needed to more accurately model sorbent durability and lifetime, which significantly affect the overall process cost of solid sorbent–based direct air capture processes.

Pilot-scale studies could also assess optimal site locations and plant configurations. Different direct air capture processes will likely be suited for specific deployment locales depending on the specific process characteristics involved (e.g., varied climates such as humid/arid, warm/cool). Furthermore, deployment location will impact operating and capital costs, which can be optimized based on the available energy resources locally. For example, if low-cost "stranded" carbon-free electricity (e.g., wind in Texas or Oklahoma) is available, then a plant could be designed with a deeper bed, which would enhance capture but increase electrical costs in the form of fan power to overcome the pressure drop. In these cases, the overall capital investment may be lower because the contactor surface area requirement may be smaller to capture the equivalent CO_2.

Public funding for demonstration projects of direct air capture are also needed to accelerate movement along the operational learning curves for existing companies and to provide incentive for new companies to enter the field. Furthermore, public funding will ensure that operational data are available to the noncommercial research community to perform independent techno-economic analyses, to guide policymakers, and to make process innovations that will lead to improved direct air capture technologies.

The availability of data about process costs and energetics will lead to optimized designs that minimize these parameters, thereby leading to more rapid deployment of efficient processes. A single agency should be designated to set guidelines for data disclosure and sharing so that data are reported in a useful, uniform way, and are sufficient for accurate analysis of process costs and energetics.

Deployment

Direct air capture processes are expected to be initially deployed near locations where suitable geological sequestration is available, limiting or removing the need to develop long-distance CO_2 pipeline networks. Broad deployment of carbon capture and sequestration from point sources will require creation of a more extensive CO_2 pipeline network, which can be leveraged by direct air capture processes if appropriately sited. Other siting factors, such as (1) the potential for locally depleting the ambient CO_2 concentration and thereby impacting agriculture or indigenous plant life, (2) proximity to appropriate sources of water when needed, and (3) proximity to renewable energy or thermal opportunities, should be considered to optimize the performance of the direct air capture plant and reduce impacts on the local communities.

Direct air capture processes may be scaled up (deployment of larger units) or scaled out (deployment of a large number of small units) to achieve necessary carbon removal targets, and it remains unclear whether one deployment mode is better than the other. Demonstration-scale plants of about 10,000 t/y CO_2 would be of sufficient size to inform optimal siting for the various approaches.

Given the scale and financial commitment (~$100M per project) required for commercial-scale direct air capture systems, public investments should only be made after detailed engineering and economics analyses (stage-gate) have been performed and demonstrate a path to commercial viability. Public investments that subsidize initial nonreoccurring engineering costs for promising direct air capture technologies could be beneficial in accelerating direct air capture technology deployment.

Implementation of the Research Agenda

Institutions

The U.S. Department of Energy's Office of Fossil Energy and National Energy Technology Laboratory (NETL) has the appropriate infrastructure to manage direct air capture research, development, and demonstration projects through a typical grant process that distributes funds to projects at universities, nonprofit research organizations, start-up companies, and large companies. Contractors that provide independent materials testing, component testing, techno-economic analysis, and professional engineering design can also be managed through the U.S. Department of Energy's existing infrastructure. For development and demonstration testing of direct air capture components and systems, a centralized facility/national testbed akin to the NETL's National Carbon Capture Center operated by the Southern Company (Figure 5.9) is recommended.

Funding

Scale of Funding

Over the past few decades, federal R&D funding as percentage of total funding has consistently shifted from demonstration and development to basic and applied research and away from industry to industry and national laboratories. To develop commercially viable direct air capture systems, funding levels will need to shift toward development and demonstration. The justification for this is as follows: It is generally accepted that the cost of scaling up a process follows the "2/3 law," where the capital cost of plant k_n at unit capacity c_n, the cost of scaling is $k_n = k_0(c_n/c_0)^{2/3}$, and k_0 and c_0 are the unit cost and capacity, respectively, of the reference plant. Assuming that a bench-scale process is 0.1 percent the capacity of a full-scale plant, pilot-scale is 1 percent of full-scale, and demonstration-scale is 10 percent of full-scale; then for every \$1 spent on bench-scale development, roughly \$5 should be spent on pilot-scale, and \$20 on demonstration-scale.

Timing of Funding

Today, the maturity of direct air capture technologies spans the spectrum from basic materials research to pre-commercial system development and demonstration. To build a pipeline of technology from basic and applied research through deployment of systems, the committee recommends staggered funding, with an early focus on R&D that transitions to demonstration and deployment projects over a period of 15 years, as depicted in Figure 5.10. Each phase of funding should have stage-gates with technical and economics metrics. Notably, before funds are committed for demonstration-scale projects, detailed third-party engineering and economic assessments must demonstrate the potential for achieving CO_2 removal at a cost of < \$300/t.

Data Management

Data collection, organization, and public release is a critical component of a modern direct air capture research agenda. A central repository should be established to house the materials data as well as the results of engineering analyses and testing of direct air capture. In addition, standard engineering assessment methodologies should be developed, analogous to Matuszewski, 2014.

FIGURE 5.9 National Carbon Capture Center, Wilsonville, Alabama.
NOTES: Funded by the Office of Fossil Energy, U.S. Department of Energy, and operated by the Southern Company Services. Award No: DE-NT0000749, period: Oct 2008–Sep 2014, funding: $251M, federal: $200M; and Award No: DE-FE0022596, period: Jun 2014-May 2019, funding: $187M, federal: $37M.
SOURCE: NCCC, 2017.

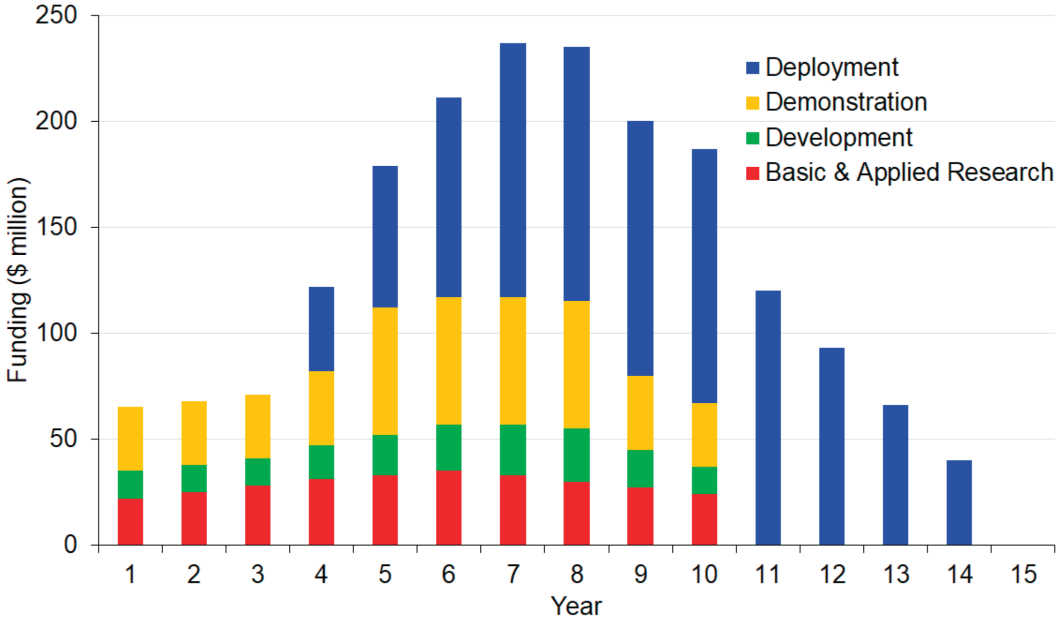

FIGURE 5.10 Recommended annual U.S. federal funding allocations for basic and applied research, demonstration, development, and deployment of direct air capture technology.

CHAPTER SIX

Carbon Mineralization of CO_2

Carbon mineralization is an emerging approach to remove carbon dioxide (CO_2) from the air and/or store it in the form of carbonate minerals such as calcite or magnesite. Mineralization occurs naturally during weathering of silicate materials (e.g., olivine, serpentine, and wollastonite) and rocks rich in Ca and Mg, particularly peridotite, which composes Earth's upper mantle and basaltic lava formed by partial melting of the upper mantle. The glossary provides short definitions for these and other geological terms.

This chapter reviews the kinetics of carbon mineralization and the major pathways for capturing and storing CO_2, discusses the amount and cost of CO_2 that could potentially be stored, and lays out a research agenda. The carbon mineralization methods described in this chapter include those that store enriched CO_2 in carbonate minerals as well as those that both remove CO_2 from air and store it in carbonate minerals. The methods reviewed here emulate and accelerate spontaneous, natural processes, making use of the abundant chemical potential energy that is available where rocks from Earth's deep interior are emplaced at and near the surface, where they are far from equilibrium with the atmosphere and hydrosphere. Because they utilize this naturally available chemical energy, these methods may offer a low cost means to mitigate greenhouse gas emissions. And because the CO_2 is locked into solid carbonate minerals, storage has a strong potential to be permanent and nontoxic.

INTRODUCTION

Storing CO_2 via reaction with common silicate rocks and minerals has been considered for almost 30 years (Lackner et al., 1995; Seifritz, 1990). More recently, the possibility of carbon mineralization using alkaline industrial waste products such as steel slag has been added to the palette of options (e.g., Gadikota et al., 2015; Huijgen et al., 2007; Pan et al., 2012; Sanna et al., 2014). Below the Committee summarizes carbon mineralization reactions and methods for capturing and storing CO_2 in carbon minerals.

Carbon Mineralization

In general, the extent of mineral carbonation depends on (1) available CO_2 dissolved in solution, (2) available alkalinity in solution, and (3) chemical conditions that foster available alkalinity via mineral dissolution and carbonate precipitation. Although low pH accelerates mineral dissolution (e.g., Pokrovsky et al., 2004) and higher pH favors carbonate precipitation (e.g., Harrison et al., 2013), experiments have demonstrated that silicate dissolution and carbonate precipitation can be combined in a single step (Chizmeshya et al., 2007; Gadikota et al., 2015; O'Connor et al., 2005).

A key source of alkalinity for Mt to Gt storage of CO_2 via carbon mineralization is Mg-rich, Ca-bearing, highly reactive rocks from Earth's deep interior, including mantle peridotite, basaltic lava, and ultramafic intrusions. Such rocks are rich in olivine and pyroxene minerals. The mineral wollastonite ($CaSiO_3$) reacts more rapidly than olivine and pyroxene, but it is not found in large quantities and has a limited geographical distribution.

In carbon mineralization, CO_2 reacts with minerals rich in Ca and Mg to form carbonates, such as calcite ($CaCO_3$), magnesite ($MgCO_3$), and dolomite ($CaMg(CO_3)_2$), and often quartz (SiO_2). Some idealized reactions are as follows:

wollastonite	$CaSiO_3 + CO_2 \rightarrow CaCO_3$
olivine	$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$
pyroxenes	$CaMgSi_2O_6 + 2CO_2 \rightarrow CaMg(CO_3)_2 + 2SiO_2$
serpentine polytypes	$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$
brucite	$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$

Wollastonite, olivine, and brucite react relatively rapidly, as do fibrous serpentines with high surface area to volume ratios, such as asbestiform chrysotile. Ca and Mg in alkaline industrial wastes react at about the same rate as wollastonite. A more extensive discussion of kinetic data for carbon mineralization appears below (see section "Carbon Mineralization Kinetics").

These reactions are spontaneous and exothermic; carbonate minerals are the "ground state" for CO_2 in near-surface rock systems such as Mg-Ca-C-O-H and Mg-Ca-Si-C-O-H (Figure 6.1).

Methods for Capturing and Storing CO_2

Carbon mineralization methods are either aimed at storing CO_2 in carbonate minerals (referred to as *solid storage*) or both removing CO_2 from air and storing it in carbonate minerals (referred to as *combined mineral capture and storage*). *Solid storage* can be accomplished in three ways:

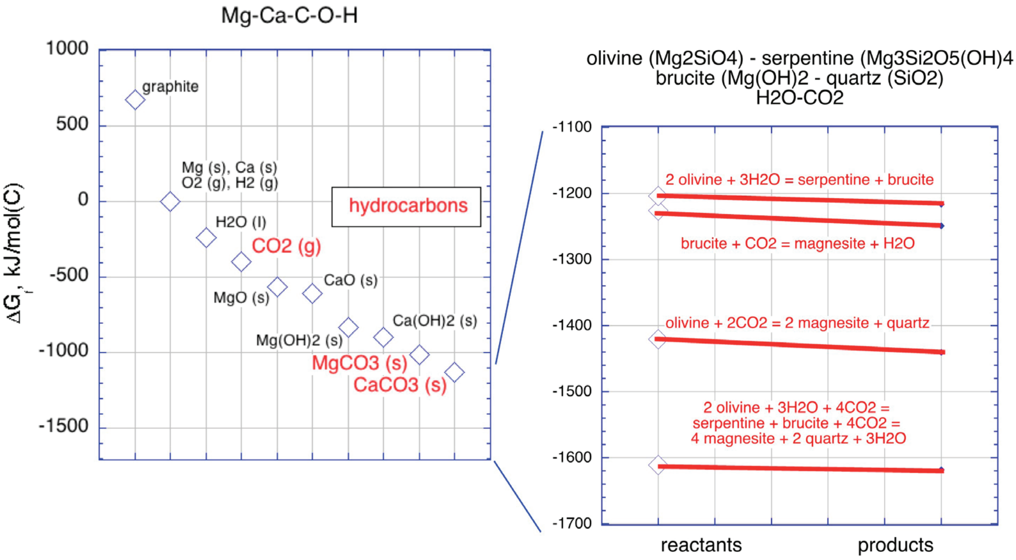

FIGURE 6.1 Standard state Gibbs free energies of formation and reaction for selected compounds in the chemical systems Mg-Ca-C-O-H and Mg-Ca-Si-C-O-H.
NOTE: The rectangle labeled "hydrocarbons" encompasses the range of Gibbs free energies of formation for common hydrocarbon species (e.g., methane, ethane, and butane) per mole of carbon.

1. *ex situ* carbon mineralization—solid reactants are transported to a site of CO_2 capture, then reacted with fluid or gas rich in CO_2,
2. *surficial* carbon mineralization—CO_2-bearing fluid or gas is reacted with mine tailings, alkaline industrial wastes, or sedimentary formations rich in reactive rock fragments, all with a high proportion of reactive surface area, and
3. *in situ* carbon mineralization—CO_2-bearing fluids are circulated through suitable rock formations at depth.

Combined mineral capture and storage may be accomplished through surficial or in situ carbon mineralization processes discussed above, using natural surface waters rather than fluids enriched in CO_2. These methods most closely emulate natural processes of CO_2 uptake. In contrast, direct air capture systems require additional technologies and energy input for CO_2 storage.

Laboratory research on ex situ carbon mineralization has been relatively extensive, but studies to date have used a wide range of reagants and conditions, making it difficult to compare results. Research on surficial carbonation of mine tailings and other fine-grained solid reactants is at an intermediate scale of readiness, ripe for larger scale field experiments. In situ carbon mineralization CO_2 storage in basaltic rocks has been studied in two medium-scale experiments and warrants further exploration at the scale of Mt/y CO_2. Natural examples of extensive in situ mineral capture and storage in ultramafic rocks, rapid reaction rates in laboratory studies, and the potential for permanent storage of hundreds of trillions of tons of CO_2 warrant continued basic research into this little-studied, high-risk, high-reward opportunity.

Mineral capture and storage using mine tailings can be implemented at a low cost but has a limited capacity. Strikingly, mining and grinding rock for the purpose of mineral capture and storage potentially has about the same cost as direct air capture systems, within uncertainties for both. In situ mineral capture and storage potentially has a lower cost than surficial methods, and a giant storage capacity, but involves uncertain feedbacks between permeability, reactive surface area, and reaction rate, and so remains a topic of basic, theoretical research.

Pumping is a substantial cost for mineral capture involving natural, CaOH-rich alkaline water in peridotite aquifers or water in CO_2 exchange equilibrium with air, due to low concentrations of dissolved carbon species. In such cases, mineralization requires co-location with geothermal power plants and/or significant thermal gradients to drive convection. Surficial mineral capture would generate many km^3 of rock products per Gt of CO_2 per year, posing potential transport and storage problems. Furthermore, the size, injectivity, permeability, geomechanics, and microstructure of key subsurface reservoirs for in situ mineral capture and storage remain almost entirely unexplored.

CARBON MINERALIZATION KINETICS

Surprisingly, despite a plethora of recent reviews of various aspects of ex situ mineral carbonation (Gadikota et al., 2015; Pan et al., 2012; Power et al., 2013a, 2013c; Sanna et al., 2014), there have been few comparisons of carbon mineralization rates, as a function of temperature, partial pressure of CO_2 [$P(CO_2)$], and other key variables. One reason for this is the ongoing pursuit of parallel lines of inquiry, involving (1) a single reaction step, combining CO_2-rich fluid with solid reactants, (2) a two-stage process, involving dissolution of solid reactants—typically at low pH—followed by introduction of CO_2 and precipitation of carbonate minerals—typically at high pH, and (3) pretreatment of solid reactants, for example by rapid heating. Nevertheless, in the two-stage process, it is generally considered that mineral dissolution is the rate-limiting step, so it is possible to compare mineral dissolution rates (as an upper bound on the combined rate of two-stage processes) and full carbon mineralization rates, for example using grain size data from experiments to calculate geometric surface area (median or mean grain diameter squared x pi), and presenting rates in mass fraction per second for 50 to 70 micron grains (Kelemen et al., 2011; Matter and Kelemen, 2009).

Here, we update this comparison, incorporating new data and using units more familiar to many geoscientists (mol/(m^2s)). Figure 6.2 provides some of this information. Where necessary and possible, we use geometric surface area to calculate rates because more detailed surface area measurements are not available for many of the data sets we wish to compare. Huge variability in measured rates—with consistency among different experiments on the same set of fluid and mineral reactants—suggests that the uncertainty in surface area is of relatively minor importance in this type of comparison. Because of time constraints, there is no comparable review in this report of rates as a function of temperature, P(CO_2) and other factors for alkaline, industrial waste materials.

After experiments indicated that wollastonite ($CaSiO_3$) was among the fastest reacting silicates (e.g., O'Connor et al., 2005), some groups have focused on carbonation of this mineral. Indeed, it may be a reasonable analogue for carbonation of calcium silicates in industrial wastes, such as steel slag for example. However, the U.S. Geological Survey (USGS) website for wollastonite (U.S. Geological Survey, 2018d) indicates that less than 1M tons of natural wollastonite per year were produced in 2016 and 2017, from global reserves estimated to be approximately 100M tons. Economic wollastonite deposits are restricted almost entirely to narrow "skarns," formed by reaction between granitic magmas and limestone or marble host rocks. The USGS reserve estimate for wollastonite includes data on skarns that are profitable to mine at \$200-350/t of wollastonite (depending on purity and crystal shape) plus income due to sale of byproducts. When fully carbonated, a ton of wollastonite can store 0.33 tons of CO_2, so these costs correspond to \$600-1,000/tCO_2. Even if these are the only costs of CO_2 storage using wollastonite, these costs are more than 10 times higher than the cost of storing CO_2 in subsurface pore space (\$10-20/t). This is not surprising. Typical costs for hard rock mining in large deposits are approximately \$10/t of rock. For smaller mines, the cost is higher. If a deposit contains less than 10 percent wollastonite, the extraction cost will be more than \$100/t. Thus, looking beyond skarns, marbles with minor amounts of wollastonite formed by prograde metamorphism are not a practical source of wollastonite for carbon mineralization.

Because olivine, $(Mg,Fe)_2SiO_4$, reacts with CO_2-bearing fluids almost as rapidly as wollastonite, it is the most important mineral constituent of the upper mantle. Olivine remains a major constituent of partially hydrated (serpentinized) peridotite massifs

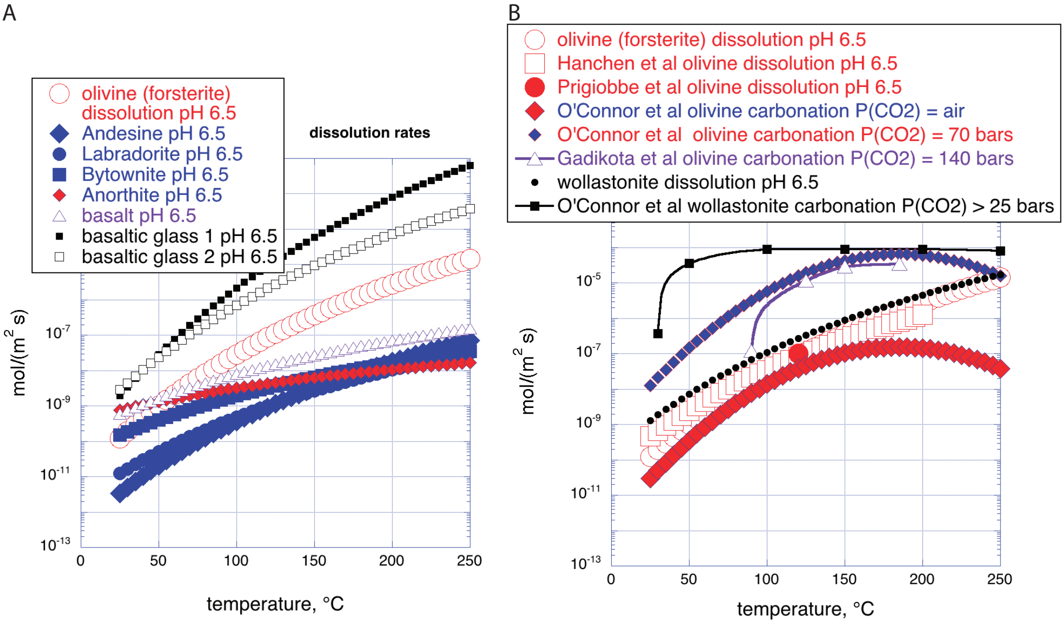

FIGURE 6.2 Comparison of different mineral dissolution and carbonation rates, as a function of temperature and P(CO_2).
NOTES: All panels have the same horizontal and vertical axis ranges, a linear temperature range of 0 to 250°C, and a logarithmic range of rates from 10^{-13} to 10^{-2} mol/(m^2s). Red open circles in all four panels are dissolution rates of Mg-endmember olivine (forsterite) at pH 6.5 based on fit to compiled data by Palandri and Kharaka, 2004.

Panel A: Rates of mineral carbonation and dissolution: "Hanchen et al olivine dissolution pH 6.5" and "Prigiobbe et al olivine dissolution pH 6.5": steady state dissolution of San Carlos olivine (91% forsterite) in CO_2-bearing aqueous fluid at pH 6.5 (Hanchen et al., 2006, 2008; Prigiobbe et al., 2009). "O'Connor et al olivine carbonation": Fit to data of O'Connor et al., 2005 by Kelemen and Matter, 2008 for carbonation of olivine (91% forsterite) at different partial pressures of CO_2, in 1M NaCl, 0.64M $NaHCO_3$ aqueous fluid in 1 hour at pH ~ 6.5. "Gadikota et al olivine carbonation": Full carbonation of olivine at different partial pressures of CO_2, in 0.64M $NaHCO_3$ aqueous fluid, with and without NaCl over 3 hours at pH ~ 6.5 (Gadikota et al., 2014). "Wollastonite dissolution pH 6.5", calculated from Palandri and Kharaka, 2004. "O'Connor et al wollastonite carbonation": Full carbonation of wollastonite at different partial pressures of CO_2, in 1M NaCl, 0.64M $NaHCO_3$ aqueous fluid (O'Connor et al., 2005).

Panel B: Rates of mineral carbonation at elevated P(CO_2) in aqueous fluid with 1M NaCl and 0.64M $NaHCO_3$ for 3 hours (Gadikota et al., 2018), allowing direct comparison of carbon mineralization rates for olivine (Figure 6.2A), plagioclase feldspar (labradorite, with a molar Ca/(Ca+Na) ratio of 0.54), a rock composed of plagioclase feldspar, olivine, and iron oxides (anorthosite, with a molar Ca/(Ca+Na) ratio in plagioclase of 0.98 and a molar Mg/(Mg+Fe) ratio in olivine of 0.66) and a basaltic lava (molar Ca/(Ca+Na) 0.60, molar Mg/(Mg+Fe) 0.48). NOTE: Carbon mineralization rates for basalt, olivine and shale in "damp", H_2O-bearing, supercritical CO_2 are approximately the same as carbonation rates for the same materials in aqueous fluid with the same P(CO_2) (Loring et al., 2011, 2013; Schaef et al., 2011, 2013).

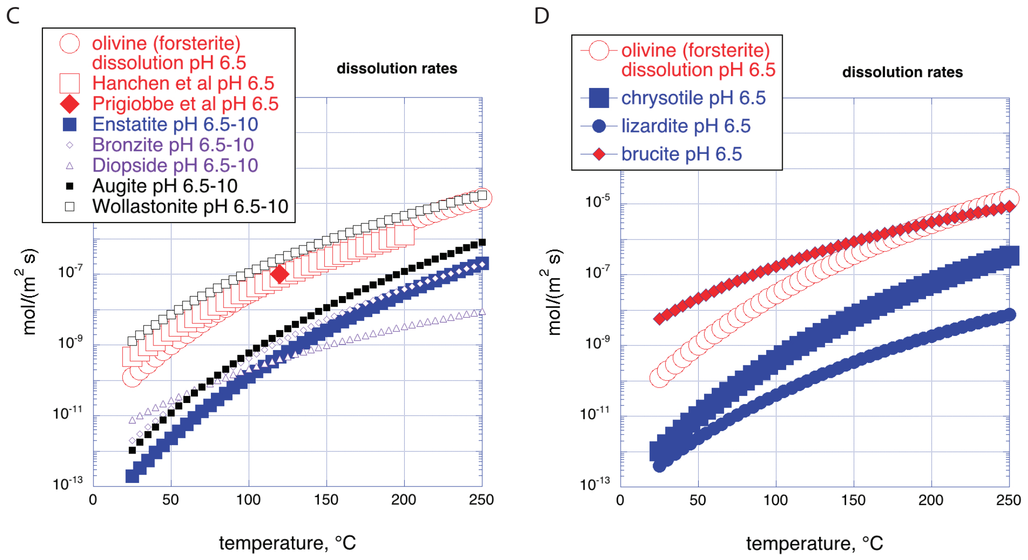

FIGURE 6.2 Continued

Panel C: Comparison of steady state aqueous fluid dissolution rates at pH 6.5 for plagioclase feldspar (molar Ca/(Ca+Na) in andesine 30-50%, labradorite 50-70%, bytownite 70-90%, anorthite 90-100%), and olivine (Fo molar Mg/(Mg+Fe) 100%), calculated from fits to compiled data by Palandri and Kharaka, 2004, for a basaltic lava fit to their experimental data by Schaef and McGrail, 2009, and for two basaltic glasses fit to their experimental data by Gislason and Oelkers, 2003.

Panel D: Comparison of steady state dissolution rates (Palandri and Kharaka, 2004) for olivine Mg-endmember forsterite at pH 6.5 and alteration products of olivine. The alteration minerals are two polymorphs of serpentine, chrysotile and lizardite, and brucite ($Mg(OH)_2$).

exposed at Earth's surface, and much research has focused on this mineral. Olivine in the mantle and in ultramafic intrusions tends to contain 88 to 92 mole percent of the Mg-endmember forsterite (Mg_2SiO_4), so that simplified carbonation reactions such as those below (see "Carbon Mineralization Kinetics") often omit discussion of the Fe-endmember fayalite.

Engineered "pH swing" methods (e.g., Park and Fan, 2004) were thought to be essential for olivine carbonation because of the perceptions that (a) aqueous fluids with high $P(CO_2)$ have intrinsically low pH, too low for extensive carbonate precipitation, and (b) olivine dissolves slowly at neutral to high pH. Breakthrough experiments by O'Connor et al., 2005 showed that using $NaHCO_3$ to buffer pH (to ~ 6.5 at experimental conditions) yielded rapid olivine carbonation. As concentrations of $NaHCO_3$ before and after experiments were approximately the same in these and subsequent, similar experiments (Chizmeshya et al., 2007; Gadikota et al., 2014), it is apparent that $NaHCO_3$

is not a net source of carbon to form carbonate minerals, but instead acts as a kind of catalyst. Dissolved $NaHCO_3$ buffers pH in a range where both olivine dissolution and carbonate precipitation are relatively rapid. In turn, it is thought that carbonate precipitation provides a continuous sink for dissolved Mg and maintains a high olivine dissolution rate in experiments (Gadikota et al., 2014), even at low water/rock ratios. In natural systems, and proposed, engineered, in situ carbon mineralization involving subsurface reaction of CO_2-bearing fluids with olivine-rich rocks, use of $NaHCO_3$ would probably not be required to achieve the same effect, because reaction path modeling has repeatedly shown that low pH, CO_2-rich fluids reacting with olivine-rich (ultramafic) rocks are rapidly buffered to high pH (e.g., Bruni et al., 2002; Paukert et al., 2012) in a spontaneous pH swing.

Another important characteristic of olivine carbonation experiments has been the lack of observed passivation. Although an SiO_2-rich layer on the surface of partially dissolved olivine has been observed (Bearat et al., 2006; Chizmeshya et al., 2007), and might cause slowing of reaction rates over time, this is not borne out in the results of time-series experiments. Figure 6.3 shows our new plot of time series experiments by O'Connor et al., 2005, Gadikota et al., 2014, and Eikeland et al., 2015. Although the data sets show slightly different rates, each can be fit with a constant rate of olivine carbonation, continuing until olivine is greater than 90 percent consumed, illustrating that passivation does not significantly reduce olivine carbonation rates, at least for grain sizes less than approximately 100 microns. We tentatively ascribe this lack of passivation during olivine carbonation to the process of reaction-driven cracking, and/or to various related processes such as the formation of etch pits on reacting olivine surfaces as discussed later in this chapter. Another factor may be buffering of pH—by addition of NaHCO3 in experiments, by natural water/rock reactions in peridotite—which has been observed to suppress the precipitation of iron oxides, which may form passivating layers in lower pH conditions (Gadikota et al., 2014).

This lack of passivation during olivine carbonation does not appear to be common for other mineral and rock reactants. An ongoing problem in comparing carbon mineralization rates is the lack of kinetic experiments with different solid reactants with the same fluid composition. Gadikota et al., 2018 performed a series of experiments to begin to address this problem (Figure 6.2B). These data provide quantitative support for the view that, in $NaHCO_3$-rich aqueous solutions, olivine carbonation is faster than carbonation of plagioclase feldspar, mafic intrusions (anorthosite, 55 wt% plagioclase feldspar, 35% olivine, 5% pyroxene, 3% Fe-oxides), and basaltic lavas in general (~ 0 to 20% olivine, 0 to 40% pyroxene, ~ 60% plagioclase feldspar). Importantly, carbonation rates for all reactants except olivine decreased with time, presumably due to passivation. This may indicate that passivation will be a problem in engineered systems—ex

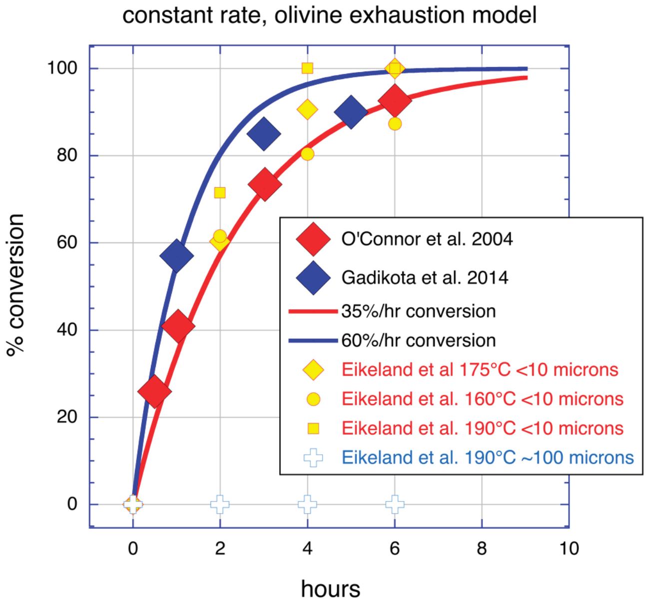

FIGURE 6.3 Time series for carbonation of olivine (91 mole % forsterite at 185°C, P(CO_2) 140 bars, average grain size ~ 50 microns, aqueous fluid with 1M NaCl and 0.64M $NaHCO_3$ (Gadikota et al., 2014; O'Connor et al., 2005), fit with constant rates of olivine consumption. (See Gadikota et al. for grain size evolution.) The fits suggest that passivation of surfaces is not significant in olivine carbonation under these conditions. Data of Eikeland et al., 2015; 100% forsterite olivine, 0.75M NaCl, 0.5M $NaHCO_3$ with grain size < 10 microns are consistent with previous data, whereas their ~100 micron fraction did not react. Based on Gadikota et al., 2014, the Committee infers that the lack of reaction in the 100 micron experiments of Eikeland et al. probably was not due to grain size alone. Gadikota et al. observed passivation of ground olivine in the years between the experiments of O'Connor et al., 2005 and their experiments, indicating that subtle surface effects can affect the reaction rate.

situ or in situ—requiring extensive carbonation of Mg and Ca in basaltic reactants with abundant plagioclase feldspar and pyroxene minerals, and relatively little olivine.

The data in Figure 6.2C illustrate the basis for the widely held view that olivine-rich ultramafic rocks such as mantle peridotite dissolve faster than basalt and the plutonic equivalent of basalt, gabbro. Basalt and gabbro are rich in alumino-silicate minerals such as plagioclase feldspar with molar Ca/(Ca+Na) less than 80 percent (most commonly, labradorite, with molar Ca/(Ca+Na) from 50 to 70%), low solubilities in aqueous fluids, and slow intracrystalline diffusion. However, the data also illustrate that amorphous basaltic glass is an important exception to the rule that peridotite reacts faster than basaltic lava. Amorphous glass forms when portions of basaltic lava flows cool faster than the time required for nucleation and growth of crystals. Basaltic lava formations with abundant glassy horizons could provide exceptionally good reactants for carbon mineralization. We are not aware of regional compilations of glass abundance and distribution in basaltic lavas, but because glass forms where basalt cools very quickly, it is likely that glass is most abundant in lavas that erupted in submarine settings (particularly hyaloclastite breccias composed of quenched fragments of flow surfaces), and in cinder cones and other formations formed by explosive eruption of small lava droplets into air.

In addition to igneous rocks such as peridotite and basalt, and their constituent minerals, some alteration products of peridotite have received considerable attention as possible reactants for carbon mineralization. In the context of the broad range of rates in Figure 6.3, dissolution rate data are sufficiently similar to results of more detailed study with a variety of different fluid reactants and experimental conditions that we can succinctly summarize relative rates using the dissolution data alone, in Figure 6.2D. Serpentine minerals dissolve much more slowly than olivine, consistent with slow carbonation of another serpentine polymorph, antigorite, under conditions favoring rapid olivine carbonation. By contrast, at low temperature brucite dissolves much faster than olivine, consistent with many studies indicating that brucite (and some fibrous, asbestiform chyrsotile) undergoes rapid carbonation during exposure of ultramafic mine tailings to air.

Figure 6.4 compares rates of carbon mineralization at elevated P(CO_2) but at ambient surface temperatures, which are useful for evaluating proposed methods for direct capture of CO_2 from air, and for proposed storage methods such as "sparging" CO_2-rich gas through mine tailings and industrial waste heaps (Assima et al., 2013a, 2014c; Harrison et al., 2013).

Finally, recognition that mine tailings rich in serpentine are abundant, and that carbonation of asbestiform chrysotile provides the benefit of mitigating an environmental hazard, has led to remarkable number of studies of carbonation of amorphous (dehydroxylated) products of rapid heat-treatment of serpentine, as a proposed feedstock for ex situ carbon mineralization using captured CO_2 from a hydrocarbon-fueled power plant (Balucan et al., 2011; Balucan and Dlugogorski, 2013; Dlugogorski and Balucan, 2014; Fedoročková et al., 2012; Ghoorah et al., 2014; Larachi et al., 2010, 2012; Li et al., 2009; Maroto-Valer et al., 2005; Mckelvy et al., 2004; O'Connor et al., 2005; Sanna et al., 2014) or using flue gas without CO_2 capture (Hariharan et al., 2014, 2016; Hariharan and Mazzotti, 2017; Pasquier et al., 2014; Werner et al., 2013, 2014). In the studies listed in the previous sentence, heat treatment is considered a relatively minor step, in terms of cost and CO_2 production, if it is accomplished using waste heat from a power plant, which is also the site of carbon capture and ex situ mineral carbonation. Waste heat may not be sufficient if a temperature as high as 600°C is required (e.g., Liu and Gadikota, 2018). If so, the cost of heat treatment could become considerable. Use of heat treatment to increase the rate of serpentine carbonation is less relevant to methods for storage of CO_2 captured from air. Moreover, costs of CO_2 storage via ex

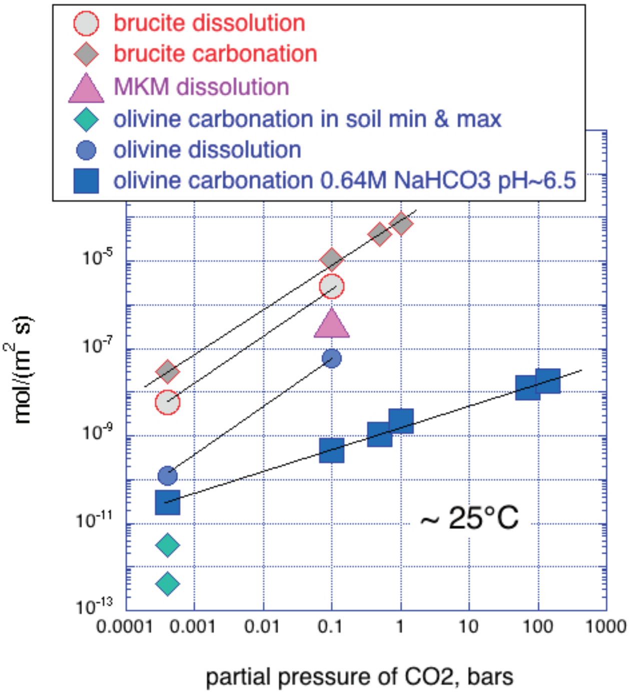

FIGURE 6.4 Low temperature dissolution and carbonation rates for minerals in mine tailings and proposed for broadcast in soils and along beaches.
NOTES: Brucite, MKM (Mt. Keith Mine, brucite-rich, serpentine mine tailings) and olivine dissolution rates at 0.1 bar $P(CO_2)$ (Greg Dipple, personal communication, 2018). Steady state dissolution rates for brucite and olivine at 0.0004 bars $P(CO_2)$ from Palandri and Kharaka, 2004. Olivine carbonation in soil: Renforth et al., 2015. Brucite carbonation: Harrison et al., 2013. Olivine carbonation 0.64M NaHCO3 pH ~ 6.5 calculated with Kelemen and Matter, 2008 fit to data of O'Connor et al., 2005 for reaction extent in 1 hour.

situ carbon mineralization using heat-treated serpentine and CO_2-rich fluids remain higher than injection of CO_2 into subsurface pore space (Table 6.1).

Conclusions

Geologically abundant olivine, in mantle peridotites and some ultramafic intrusions and lava flows, together with the mineral brucite produced by hydrous alteration of olivine, provide the best reactants for in situ carbon mineralization. Wollastonite reacts faster than olivine, but it is not geologically abundant (for more information, see the section on carbon mineralization kinetics earlier in this chapter). Minerals such as typical plagioclase feldspar with molar Ca/(Ca+Na) less than 80 percent—major constituents of basaltic lithologies—react more slowly than olivine and undergo passivation at a relatively early extent of conversion. However, basaltic formations are more

TABLE 6.1 Solid Storage of CO_2 via Carbon Mineralization at Elevated P(CO_2) and/or Temperature

	Method	**Weight fraction CO_2/hr**	**t CO_2/ km^3/y**	**CO_2 reservoir production Gt rock/y**	**CO_2 reservoir Gt rock**	**Max CO_2 weight fraction in 1 y at rate in table**	**Gt/y CO_2**	**\$/t CO_2**	**References**	**Notes**
Ex situ carbon mineralization										
Peridotite and olivine	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high P(CO_2), with or without pH swing process and heat treatment	0.1-0.3		Some fraction of 0.2 Gt ultramafic tailings per year		0.1-0.5	0.02-0.1	50-100	Recent comprehensive reviews by Bodenan et al., 2014; Chizmeshya et al., 2007; Gadikota and Park, 2015; Gadikota et al., 2014; Gerdemann et al., 2007; Giannoulakis et al., 2014; Khoo et al., 2011; O'Connor et al., 2005; Pan et al., 2012; Power et al., 2013a, 2013c; Sanna et al., 2013, 2014 Fits to data by Kelemen and Matter, 2008; Kelemen et al., 2011; Matter and Kelemen, 2009	2, 3

Brucite	Sparging of elevated $P(CO_2)$, ambient temperature gas through brucite powder + H_2O	0.03-0.3	Some fraction of 0.2	0.03-0.1	0.01-0.02	~ 10–20?	Harrison et al., 2013	2
Brucite	Manufacture of brucite from mine tailings via reaction at elevated temperature with $NaOH$-H_2O solution, plus sparging with CO_2-rich gas	0.3?	Some fraction of 0.2	0.03-0.1	0.01-0.02	200-600	Madeddu et al., 2015	2
Serpentine	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high $P(CO_2)$, with or without pH swing process and heat treatment	Much slower than olivine	Some fraction of 0.2	0.03-0.1	0.01-0.02	200-600	Bodenan et al., 2014; Gerdemann et al., 2007; Huijgen et al., 2007; Khoo et al., 2011; O'Connor et al., 2005; Sanna et al., 2013, 2014	2, 4

continued

TABLE 6.1 Continued

	Method	Weight fraction CO_2/hr	t CO_2/ km^3/y	CO_2 reservoir production Gt rock/y	CO_2 reservoir Gt rock	Max CO_2 weight fraction in 1 y at rate in table	Gt/y CO_2	\$/t CO_2	References	Notes
Serpentine	Elevated temperature and pressure reaction with flue gas or water saturated in flue gas, and/or with prior heat treatment	Still slower than olivine, passivation problems		Some fraction of 0.2		0.03-0.1	0.01-0.02	200-600	Hariharan et al., 2013; Hariharan and Mazzotti, 2017; Mazzotti personal communication, 2017; Sanna et al., 2013, 2014; Werner et al., 2011, 2013, 2014	2, 4
Wollastonite	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high P(CO_2)	0.2-0.6		0.00055	0.1	0.3	0.0002	80-160	Gerdemann et al., 2007; Giannoulakis et al., 2014; Huijgen et al., 2007; O'Connor et al., 2005; U.S. Geological Survey, 2016	1
Steel and blast furnace slag	Elevated temperature and pressure reaction with purified CO_2 or water saturated at	Faster than wollastonite		0.17-0.50		0.01-0.20	0.002-0.1	75-100	Gomes et al., 2016; Huijgen et al., 2007; Renforth et al., 2011; Sanna et al., 2013, 2014	5

	high P(CO_2), with or without pH swing process and heat treatment							
Cement waste	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high P(CO_2) ± various pretreatment steps	Faster than wollastonite	0.42-2.1	0.016-0.25	0.001-0.3	Probably steel slag cost divided by ratio of weight fraction CO_2 for steel slag to this commodity	Gomes et al., 2016; Renforth et al., 2011; Sanna et al., 2013, 2014	5
Construction and demolition waste	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high P(CO_2) ± various pretreatment steps	Faster than wollastonite	1.4-5.8	0.08-0.11	0.1-0.6	Probably steel slag cost divided by ratio of weight fraction CO_2 for steel slag to this commodity	Renforth et al., 2011	5

continued

TABLE 6.1 Continued

	Method	Weight fraction CO_2/hr	t CO_2/ km^3/y	CO_2 reservoir production Gt rock/y	CO_2 reservoir Gt rock	Max CO_2 weight fraction in 1 y at rate in table	Gt/y CO_2	\$/t CO_2	References	Notes
Other municipal solid waste	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high $P(CO_2)$ ± various pretreatment steps	Faster than wollastonite		1.3		0.016-0.25	0.004-0.16	Probably steel slag cost divided by ratio of weight fraction CO_2 for steel slag to this commodity	Hoornweg and Bhada-Tata, 2012; Sanna et al., 2013, 2014	5
Coal ash in general	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high $P(CO_2)$ ± various pretreatment steps	Faster than wollastonite		0.4-0.6		0.022-0.29	0.0002-0.09	Probably steel slag cost divided by ratio of weight fraction CO_2 for steel slag to this commodity	Gomes et al., 2016; Sanna et al., 2013, 2014	5

Lignite ash	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high $P(CO_2)$ ± various pretreatment steps	Faster than wollastonite	0.03-0.06	0.03-0.10	0.0009-0.006	Probably steel slag cost divided by ratio of weight fraction CO_2 for steel slag to this commodity	Renforth et al., 2011; Sanna et al., 2013, 2014	5
Anthracite ash	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high $P(CO_2)$ ± various pretreatment steps	Faster than wollastonite	0.02-0.05	0.01-0.10	0.0002-0.005	Probably steel slag cost divided by ratio of weight fraction CO_2 for steel slag to this commodity	Renforth et al., 2011	5

continued

TABLE 6.1 Continued

	Method	Weight fraction CO_2/hr	t CO_2/ km^3/y	CO_2 reservoir production Gt rock/y	CO_2 reservoir Gt rock	Max CO_2 weight fraction in 1 y at rate in table	Gt/y CO_2	\$/t CO_2	References	Notes
Bituminous ash	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high $P(CO_2)$ ± various pretreatment steps	Faster than wollastonite		0.15-0.28		0.003-0.020	0.0004-0.006	Probably steel slag cost divided by ratio of weight fraction CO_2 for steel slag to this commodity	Renforth et al., 2011	5
Red mud, residue of Al_2O_3 extraction from bauxite	Elevated temperature and pressure reaction with purified CO_2 or water saturated at high $P(CO_2)$ ± various pretreatment steps	Faster than wollastonite		0.12		0.04-0.07	0.00001-0.006	~150	Gomes et al., 2016; International Aluminium Institute, 2018; Sanna et al., 2014	5

Other alkaline wastes, mostly produced at rates less than 0.01 Gt per year									See comprehensive list in Sanna et al., 2014	
Ultramafic mine tailings at ambient temperature										
Ultramafic mine tailings	Sparging CO_2-rich gas through mine tailings	0.03-0.30	1E8-1E9	0.200		0.03-0.10	0.006-0.02	10-30	Assima et al., 2013a; Harrison et al., 2013; U.S. Geological Survey, 2018a, b, c	
In situ mineral carbonation										
Peridotite	Drill to depth where temp > 90°C, inject CO_2-rich fluid at $P(CO_2) > 60$ bars	0.1-0.3	3E8-1E9	1-100	1E5-1E8	0.1-0.6	0.1-60	10-30	Kelemen and Matter, 2008; Kelemen et al., 2011, 2016; Matter and Kelemen, 2009	6

continued

TABLE 6.1 Continued

	Method	Weight fraction CO_2/hr	t CO_2/ km^3/y	CO_2 reservoir production Gt rock/y	CO_2 reservoir Gt rock	Max CO_2 weight fraction in 1 y at rate in table	Gt/y CO_2	\$/t CO_2	References	Notes
Basaltic lava, specific CarbFix and Wallula sites	Drill to depth where temp > 25°C, inject CO_2-rich fluid at $P(CO_2) > 60$ bars	>0.0003 at CarbFix, ~ 0.001 at Wallula	>10,000	0.00003		0.01-0.25	3E7-8E6	10-30	Aradóttir personal communication 2017; Gislason and Oelkers, 2014; Matter et al., 2016; Sigfusson et al., 2015; Xiong et al., 2018	6
Basaltic lava, global on-land flood basalts	Drill to depth where temp > 25°C, inject CO_2-rich fluid at $P(CO_2) > 60$ bars			1-100	1E5-1E6	0.01-0.25	0.01-25	10-30	McGrail et al., 2017a for Columbia River Basalt and Deccan Trapps, plus our extrapolation to include Siberian Trapps, Karoo Basalts, Afar Volcanic Province, and Parana Basalts	7

Basaltic lava, global, submarine, suitable sites with sedimentary cap rocks	Drill to depth where temp > 25°C, inject CO_2-rich fluid at $P(CO_2) > 60$ bars		1-100	8E4-4E5	0.01-0.25	0.01-25	200-400	Goldberg and Slagle, 2009; Goldberg personal communication, 2017	7

NOTES:

1. USGS estimates for production and global resource.

2. Production and CO_2 capacities assuming that peridotite, olivine, brucite, and/or serpentine are derived from serpentinized, ultramafic mine tailings. If ultramafic rock were mined and milled for the purpose of CO_2 storage, then the storage reservoir becomes 100s of millions to 100s of billions of tons of rock, multiplied by the CO_2 weight fraction achieved by a specific storage process, and the additional cost is $10/t divided by the CO_2 weight fraction captured.

3. Little or no evidence for olivine passivation with reaction progress; almost 100% carbonation obtained within a few hours.

4. Reduces asbestos content of mine tailings.

5. Commonly reduces environmental hazards of alkaline waste products.

6. Ignores possible negative feedbacks, destruction of permeability, and armoring of reactive surface areas via carbonate crystallization, much more significant for peridotite with initial porosity ~1% than for basaltic lava with initial porosity > 10%.

7. Assumes CO_2 injection into 10% pore space in submarine lava flows, eventually followed by carbon mineralization.

abundant than ultramafic rocks, and are present in huge volumes relatively close to some population centers. For in situ carbon mineralization, where it may be possible to access vast amounts of rock via injection into high-porosity, high-permeability lava flows, the local rate and total extent of reaction may not be limiting factors.

In altered ultramafic rocks, the minor mineral brucite (0 to 10% by weight), together with asbestiform chrysotile serpentine, provides the best reactant for combined mineral capture and solid storage at low-temperature, near-surface conditions, for example in mine tailings. For solid storage alone, sparging CO_2-rich gas through mine tailings and perhaps alkaline industrial wastes could yield up to million-fold accelerations in carbon mineralization rates, compared to uptake of CO_2 from air in unmodified tailings.

Because the Ca-bearing component in many alkaline industrial waste products is similar in composition to the rapidly carbonating mineral wollastonite (Figure 6.2A), but less fully crystalline and thus potentially faster to dissolve and react, alkaline wastes are likely to react somewhat faster than the minerals whose kinetic data have been summarized here. However, relatively low Ca and Mg concentrations in some industrial wastes limit the CO_2 storage capacity per ton of solid reactant (Table 6.1).

Finally, where basaltic lava formations contain horizons rich in amorphous glass, these react more rapidly than olivine, and provide excellent targets for in situ mineral carbonation. Basaltic glass can also provide exceptionally good material for ex situ mineral carbonation.

EX SITU CARBON MINERALIZATION

An influential review by Mazzotti et al., 2005 concluded that known methods for ex situ carbon mineralization, coupled with CO_2 capture from flue gas and other point sources, were too expensive for implementation at scale. For example, they estimated that such processes would approximately double the cost of electricity from a coal-fired power plant. Recent review papers (Gadikota and Park, 2015; Giannoulakis et al., 2014; Huijgen et al., 2007; Khoo et al., 2011; Sanna et al., 2014) confirm that CO_2 storage via ex situ carbon mineralization remains significantly more expensive than storage of supercritical CO_2 in deep sedimentary formations. (A generic estimate of energy requirements appears in Appendix E.) Moreover, scaling up ex situ carbon mineralization poses the problem of transporting and storing gigatons of carbonated solid material, which potentially involves large transport costs and unknown environmental impacts.

Table 6.1 lists possible solid reactants proposed for ex situ carbon mineralization. These reactants include minerals, rocks, and industrial wastes that could be combined with high-CO_2 fluids in reactors at elevated temperature and pressure. The mineral olivine, and rocks containing tens of percent olivine, such as mantle peridotite, ultramafic intrusions, and basaltic lavas, are widely available and react rapidly, and therefore are the most commonly considered solid reactants for carbon mineralization.

Many industrial processes produce alkaline waste materials, such as steel slag, construction and demolition wastes, and cement kiln dust, that are rich in metal cations and have relatively low SiO_2 and Al_2O_3 contents. These materials react readily with CO_2 to form carbonate minerals at rates comparable to, or slightly faster than, the fastest reacting natural silicate minerals (i.e., wollastonite and olivine). Peak rates for wollastonite carbonation in alkaline industrial waste are achieved at approximately 100°C (Figure 6.2A), lower than the optimal temperature for olivine carbonation (~185°C), leading to a possible cost savings (Greeshma Gadikota, personal communication, 2017). Cumulative annual production rates of these materials, excluding mine tailings (discussed below), are estimated to have a total CO_2 uptake capacity of 0.5 to 1.0 Gt/y (e.g., Renforth et al., 2011; Sanna et al., 2014).

The cost of carbon mineralization is highly dependent on the path and materials used. Nonetheless, a consistent theme is that the cost for proposed CO_2 storage via ex situ mineralization is about 10 times higher than the cost of storage of injected CO_2 in subsurface pore space beneath an impermeable cap rock, even when the long-term cost of monitoring potential leaks is included for storage in pore space. For this reason, recent reviews (e.g., Gadikota et al., 2015; Huijgen et al., 2007; Pan et al., 2012; Sanna et al., 2014) focus on producing value-added materials that can be sold, to offset some or all of the cost of the CO_2 capture and mineralization process. In particular, the focus falls on building materials, because these are used at a global rate exceeding 10 Gt/y and involve storage for decades to centuries. Gadikota et al. (2015) write, "Replacing 10% of building materials with minerals carbonated with anthropogenic CO_2 [could] reduce CO_2 emissions by 1.6 Gt/year." One specific idea is to use a significant fraction of carbonated material, produced by ex situ reaction of CO_2 with minerals or industrial waste, as aggregate in concrete. Given that the carbonation process adds cost, compared to other sources of aggregate for concrete, research focuses on the possibility of producing aggregate that has added, desirable properties in the final concrete product (e.g., Gadikota et al., 2015). Another idea is to use the reaction products in the supply chain for conversion of CO_2 to methane (CH_4) and more complex hydrocarbons.

Carbon capture, utilization, and storage is the subject of a separate National Academies of Sciences, Engineering, and Medicine study.[1]

ENHANCED CARBONATION OF ULTRAMAFIC MINE TAILINGS AND SEDIMENTS

Mine tailings provide "low-hanging fruit" as rock reactants for CO_2 removal from air and for CO_2 storage via carbon mineralization, because of their high surface area to volume ratios compared to subsurface geological formations, and because they are quarried and mined for other reasons. Fresh and, more commonly, partially serpentinized ultramafic rocks from Earth's mantle are mined for Cr and Ni. Ultramafic intrusions, with Mg to Si ratios approaching 2 and abundant olivine, are mined for platinum-group elements, Cr, and diamonds. Ultramafic lava flows (komatiites) and tectonically exposed and weathered mantle peridotites are an important source of Cr and Ni. Mafic intrusions comparable in composition to basaltic lavas are mined for platinum group elements, Cr and Ni.

Uptake capacity for complete olivine and brucite carbonation in these materials is significant: 0.62 tons of CO_2 per ton of olivine reactant, 0.76 tons of CO_2 per ton of brucite reactant, and approximately 0.4 to 0.5 tons of CO_2 per ton of pyroxene and serpentine. Based on our informal assessment of the volume of existing mines, we estimate that the total mass of existing ultramafic tailings is less than 10 billion tons, of which an unknown proportion has already been carbonated due to natural weathering processes. Annual production of new ultramafic mine tailings is about 200 million tons (Power et al., 2013c). Dipple and co-workers (Harrison et al., 2013; Power et al., 2011, 2013c; Wilson et al., 2014) emphasize that at surface conditions (~10-30°C, $P(CO_2) \sim 0.004$ atm) most minerals in ultramafic and mafic rocks are relatively slow to react, compared to brucite and some asbestiform chrysotile. Thus, they focus on rapid carbonation of labile magnesium contained in the latter two minerals. Typically, labile Mg comprises approximate 3 wt% of partially to fully serpentinized, ultramafic mine tailings, with an approximate maximum 10 wt% (Greg Dipple, personal communication, 2017). Carbonation of this Mg (~24 gm/mol) in newly produced mine tailings would consume less than 36 million tons of CO_2 per year.

Because this storage capacity is small, the question arises whether one could mine ultramafic rock for the purpose of creating fine-grained rock reactants for CO_2 mineral capture from air and storage. Quarrying, crushing, and grinding of mine tailings

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[1] See Developing a Research Agenda for Utilization of Gaseous Carbon Waste Streams, http://nas-sites.org/dels/studies/gcwu/ (accessed January 28, 2019).

cost approximately \$10/t (InfoMine, 2018). Additional costs per ton to speed carbon mineralization (e.g., spreading tailings in thin sheets, stirring them, providing access to air flow) might be negligible. Carbonating 1 to 10 wt% labile Mg, consuming approximately 2 to 18 wt% CO_2, would correspond to \$55-500/tCO_2. This cost is comparable to estimates for direct air capture systems (Chapter 5) plus subsequent storage in deep sedimentary formations (Chapter 7), within the uncertainties of all values. On the one hand, creating tailings solely to consume labile Mg for rapid CO_2 capture from air and solid storage would produce 5-50 Gt of tailings (2-17 km^3) per Gt of CO_2 captured. To put these volumes in context, this corresponds to a layer 3-30 microns thick over the 510 million km^2 area of the oceans, 0.1-1.2 millimeters thick over the 14 million km^2 of arable land worldwide, or 10-100 m thick over Washington, D.C. (177 km^2), per Gt of CO_2 captured from air and stored. Depending on location and societal preferences, transporting and storing or disposing of these tailings could be problematic.

In addition to rapid carbonation of labile Mg, some olivine and a small amount of non-asbestos serpentine in ultramafic tailings will also undergo carbonation over decades of weathering. To calculate how much, we use the data in Figure 6.4, the assumption of constant reaction rates (e.g., Figure 6.3), a brucite conversion rate (mass fraction per second) of 3 10^{-8}/s, and olivine and serpentine conversion rates that are 10^2 and 10^4 times smaller, respectively. This calculation yields the estimate that carbon mineralization of typical mine tailings with 3 wt% labile Mg (7.2 wt% brucite, 40 wt% olivine, 52.8 wt% serpentine) could capture and store about 21 wt% CO_2 in 100 years (Figure 6.5). If the cost of carbonation is not much greater than the initial cost of quarrying and grinding (~ \$10/ton of rock), this would cost \$48/tCO_2—somewhat less than the lowest estimated costs of direct air capture systems—and produce about 1.7 km^3 of tailings per Gt of CO_2 captured and stored (a 10 m layer over Washington, D.C.). However, extensive areas of thinly layered tailings would have to be maintained for many decades. It might be possible to reach a similar goal by dispersing ultramafic tailings on coastlines or onto shallow seafloor (Hartmann et al., 2013; Köhler et al., 2010, 2013; Montserrat et al., 2017; Rigopoulos et al., 2018; Schuiling and Krijgsman, 2006), but environmental impacts and barriers to social acceptance are uncertain.

Rates of ultramafic mineral carbonation at ambient surface temperatures increase with elevated CO_2 pressure (Figure 6.4), suggesting that sparging CO_2-rich gas or fluids through tailings piles could accelerate CO_2 uptake in mine tailings for *solid storage*. Given the cost estimates in the previous two paragraphs, this approach is likely to be more expensive than storage of supercritical CO_2 in sedimentary formations (about \$10-20/t; see Chapter 7), but could provide a local solution where, for example, mining companies or geothermal power plants wish to store CO_2 emitted on site and/or add value via carbon offsets.

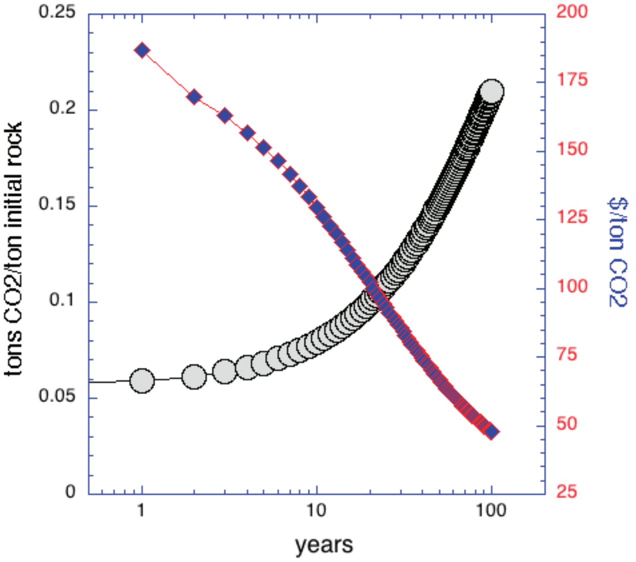


FIGURE 6.5 Weight fraction CO_2 removed from air and stored in ultramafic mine tailings with 3 wt% labile Mg, as a function of time.
NOTES: The initial rock reactant contains 7.2 wt% brucite, 40 wt% olivine, and 52.8 wt% serpentine, with constant reaction rates (mass fraction per second) of $3\ 10^{-8}$, $3\ 10^{-10}$, and $3\ 10^{-12}$, respectively. Passivation effects, and the cost of methods to ameliorate them, are not included here. Formation of crusts within a tailings pile (e.g. Wilson et al., 2014, Figure 3) and carbonate coatings on grains (e.g., Wilson et al., 2014, Figure 2) can cause passivation. Some of this could be overcome by stirring the tailings and similar low-cost methods.

Grinding ultramafic or mafic basaltic rock reactants to smaller sizes than typical of mine tailings, and spreading them in agricultural soil, forest soil, or along beaches has been suggested as a means for CO_2 removal from air (e.g., Schuiling and Krijgsman, 2006). This idea has recently been experimentally evaluated and reviewed in several papers (Beerling et al., 2018; Edwards et al., 2017; Hartmann et al., 2013; Kantola et al., 2017; Köhler et al., 2010, 2013; Meysman and Montserrat, 2017; Montserrat et al., 2017; Moosdorf et al., 2014; Renforth et al., 2015; Renforth and Henderson, 2017; Rigopoulos et al., 2018; Taylor et al., 2016, 2017; ten Berge et al., 2012). Most of these studies use olivine as the mineral reactant, because brucite and asbestiform chrysotile are not abundant in most candidate rock formations, asbestos is a serious health hazard, and most other serpentine minerals are slow to react at surface conditions (see "Carbon Mineralization Kinetics"). Some studies also consider basaltic lava as a reactant.

Carbon mineralization for different rates and grain sizes is illustrated in Figure 6.6. Carbon uptake in soils occurs through the interaction of air with dissolved alkalinity, which in some cases is known to release Ca at rates of 10^{-15} to 10^{-16} mol/(cm^2 s)

(Renforth et al., 2015). The reaction of seawater with olivine ground to about 1 micron has comparable rates (Köhler et al., 2013; Montserrat et al., 2017; Rigopoulos et al., 2018). Using the approach of Renforth (2012), an energy cost of $0.05-0.30/kWh, and $10/t for mining and crushing olivine to tailings size, we calculate that this method costs approximately $25-105/t.

Similarly, Renforth et al. (2009, 2015) have shown that carbonate precipitation in soil at brownfield sites modified with demolition rubble is 3 times higher than the value of average C content in urban areas, corresponding to a storage potential of 30 ± 10^{-2} kg CO_2 /m^2. This increase in carbonate precipitation is attributed to the leaching of alkalinity from olivine and/or Ca-rich building materials that are pulverized during demolition to increase the reactive surface area and mix within the top layer of soil.

Microbial processes may enhance weathering rates in soil, because microbial degradation of organic matter generates chelating agents and organic and inorganic acids. These microbial processes also accelerate mineral carbonation by increasing the local CO_2 partial pressure to 10-100 times atmospheric concentration (Power et al., 2009, 2013a).

These studies suggest that incorporating finely ground olivine in agricultural soils or broadcasting it into the surface ocean is sufficiently fast and inexpensive to be competitive with direct air capture systems. A concern is that minor constituents in olivine, such as Ni and Cr, could accumulate in soil or water over time. Oxidized Ni and Cr compounds in water and food constitute significant health hazards at low concentrations.

IN SITU CARBON MINERALIZATION

In situ storage—via circulation of CO_2-rich fluids (CO_2-rich water or H_2O-bearing supercritical CO_2) in appropriate formations to form subsurface carbonate minerals—addresses many of the problems of ex situ solid storage but remains a largely speculative alternative. Most investigations of in situ solid storage, and in situ capture and storage, focus on mafic and ultramafic rock formations, particularly large provinces of basaltic lava and large massifs of mantle peridotite, because of their high abundance, widespread geographical distribution, and rapid carbon mineralization rates.

Kinetic studies (see "Carbon Mineralization Kinetics") suggest that in situ carbon mineralization in ultramafic rocks (with high molar Mg to Si ratios) and in glass-rich basaltic lava flows can potentially consume tens of weight percent of injected CO_2 within a few years. Experimental studies of reaction kinetics are consistent with the results of pilot experiments on carbon mineralization in mafic and ultramafic formations, as summarized in the following sections.

It is important to add that a study estimating carbon mineralization rates in a specific sandstone in a depleted oil reservoir (Benson et al., 2005) led to the widespread impression that in situ carbon mineralization is so slow that it would not become a significant factor for large-scale storage of CO_2 for thousands of years after injection. However, this result is not applicable to carbon mineralization in basaltic lavas and ultramafic rocks (Figure 6.7; Benson, personal communication, 2017).

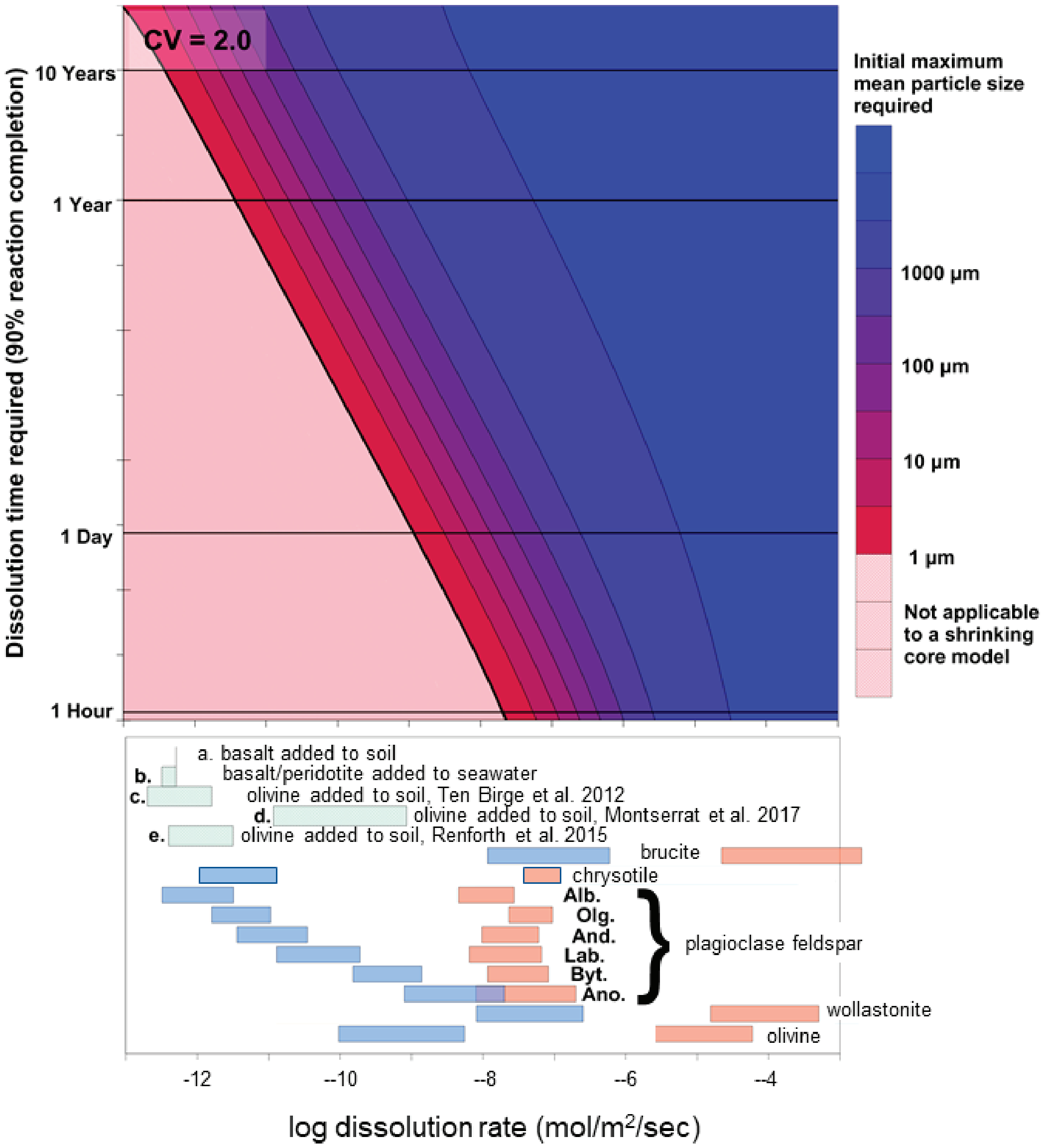
FIGURE 6.6 (Facing page) Relationship between initial mean particle size in a typical particle size distribution (covariance σ/μ, CV = 2.0), mineral dissolution rate, and time required to achieve 90% by volume dissolution of an arbitrary mineral using a shrinking core model.
NOTES: For a given extent of dissolution (*X*), the initial particle diameter (D_0; m) can be related to dissolution rate (W_r; mol m^{-2} s^{-1}) through a shrinking core model

$$X(t) = \frac{D_0^3 - (D_0 - 2W_r V_m t)^3}{D_0^3}$$

where V_m is the molar volume of the material (m^3 mol^{-1} assumed here to be 40 cm^3 mol^{-1}, although the molar volume of natural primary silicate minerals ranges from this up to >100 cm^3 mol^{-1}), and *t* is the dissolution time (s). Grinding produces a particle size range. Here we use a gamma distribution previously coupled to a shrinking core model (Gbor and Jia, 2004)

$$\mathrm{P}(D) = \frac{D^{\alpha-1} e^{-D/\beta}}{\beta^{\alpha}\Gamma(\alpha)}$$

where *α* and *β* are empirically-derived coefficients that describe the variability of particle size. A maximum mean particle size was simulated with a typical particle size distribution from comminution to achieve 90% dissolution. Dissolution rate ranges are shown for brucite ($Mg(OH)_2$), chrysotile serpentine ($Mg_3Si_2O_5(OH)_4$), minerals in the plagioclase feldspar solid solution [Na endmember albite (Alb - $NaAlSi_3O_8$), Ca endmember anorthite (Ano - $CaAl_2Si_2O_8$), oligoclase (Olg – 10-30% Ano), andesine (30-50% Ano), labradorite (Lab – 50-70% Ano), bytownite (Byt – 70-90% Ano)], wollastonite ($CaSiO_3$), and Mg-rich olivine (Mg_2SiO_4), derived using rate data from Palandri and Kharaka (2004) for all minerals except chrysotile serpentine (Thom et al., 2013), assuming pH from 3 to 7, 25°C (blue bars) and 180°C (orange bars), and negligible effects of mineral solution saturation. Rates determined from mineral dissolution experiments are shown for (a) basalt added to artificial soil (~10°C; Manning et al., 2013), (b) basalt/dunite/hazburgite added to seawater (25°C, Rigopoulos et al., 2018), (c) Mg-rich olivine added to soil (25°C, ten Berge et al., 2012), (d) Mg-rich olivine added to seawater (25°C Montserrat et al., 2017), and (e) Mg-rich olivine added to soil (19°C, Renforth et al., 2015). Figure and calculations courtesy of Phil Renforth, personal communication, 2018.


CV = 2.0
Dissolution time required (90% reaction completion)
10 Years
1 Year
1 Day
1 Hour
Initial maximum mean particle size required
1000 μm
100 μm
10 μm
1 μm
Not applicable to a shrinking core model
a. basalt added to soil
b. basalt/peridotite added to seawater
c. olivine added to soil, Ten Birge et al. 2012
d. olivine added to soil, Montserrat et al. 2017
e. olivine added to soil, Renforth et al. 2015
brucite
chrysotile
Alb.
Olg.
And.
Lab.
Byt.
Ano.
plagioclase feldspar
wollastonite
olivine
-12
-10
-8
-6
-4
log dissolution rate (mol/m2/sec)

In situ Carbon Mineralization in Basalt

The committee's November 2017 workshop included two presentations on *in situ* carbon mineralization experiments in basalt: the ongoing CarbFix experiment in Iceland and the recently completed Wallula Project in Washington State. Both experiments involved extensive characterization of the composition, structure, and hydrology in thick sequences of basaltic lavas, followed by injection of CO_2-rich fluids to investigate storage in pore space and as solid carbonate minerals. The following information is derived from these presentations and from published reviews of CarbFix (e.g., Aradóttir et al., 2011; Gislason et al., 2010; Gunnarsson et al., 2018; Matter et al., 2011, 2016; Snæbjörnsdóttir et al., 2017) and Wallula (e.g., McGrail et al., 2014, 2017a, 2017b).

The Wallula project injected 977 tons of water-saturated, supercritical CO_2 at a depth of 828 to 886 meters. Side cores from the main borehole wall revealed the presence of abundant, newly formed carbonate minerals precipitated by reaction of the basalt with injected CO_2, consistent with the composition of water in the borehole. Extensive surface studies and borehole observations for several years revealed no leakage of CO_2 from the highly permeable horizon into which it was injected. Via experiments on drill core from the same basalt formation as the host for the Wallula injection, Xiong

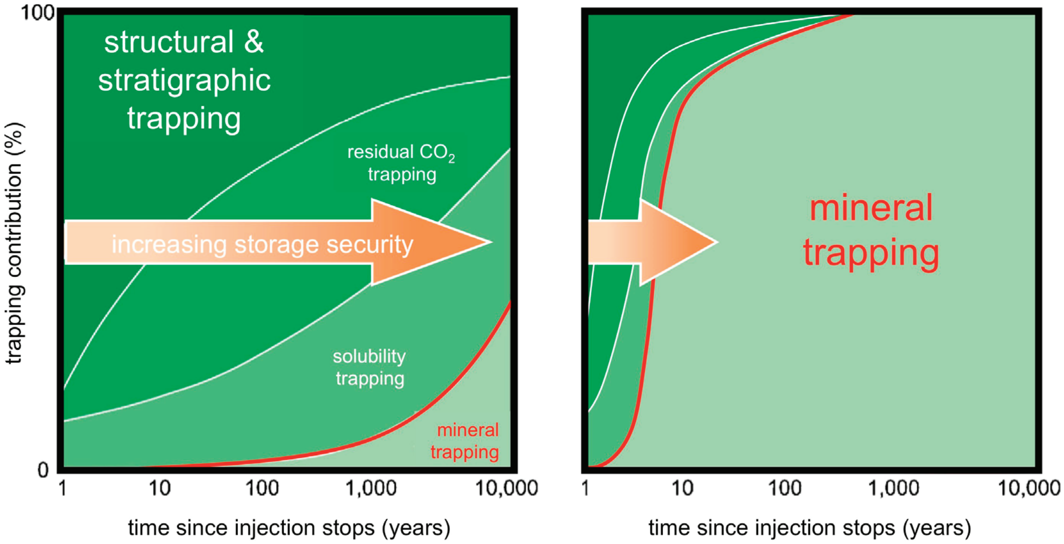


FIGURE 6.7 Modified versions of Figure 5.9 in Benson et al., 2005.
NOTES: Secondary trapping mechanisms vary widely depending on geology, structure, and hydrology. Lefthand panel, typical sedimentary reservoir, after Krevor et al., 2015. Right hand panel, peridotite reservoir, approximated using data from Figure 6.5.

et al. (2018) inferred a CO_2 mineralization rate of 0.04 wt%/y (mass fraction of ~ 10^(-11)/s) for this site, consistent with other laboratory experiments on basalt and its constituent minerals, discussed above, and the observed rate of carbon mineralization at CarbFix, estimated below. Over the time span of several years to decades, passivation of reactive surfaces may decrease the mineralization rate. For this and other reasons, it is not known how much of the injected CO_2 formed carbonate minerals, and how much still remains within fluid in pore space at the Wallula site.

The CarbFix experiment is being conducted by the geothermal power company Reykjavik Energy, together with a consortium of research scientists. In addition to investigating proposed methods for CO_2 storage, this project has the goal of storing CO_2 and hydrogen sulfide co-produced with geothermal fluid at a specific power plant. Phase I of CarbFix injected about 200 tCO_2 into highly permeable, fractured basalts at a depth of 500 m (ambient temperature ~ 20-50°C, porosity ~ 10%). At this depth, CO_2 solubility in water is not high, and CO_2 rich fluids are not supercritical. As a result, the project employs the novel technique of separately injecting H_2O and CO_2 with proportions adjusted to ensure complete solubility of CO_2 into aqueous fluid at the target depth (Figure 6.8). This technique is known as solution trapping.

CarbFix also used a novel tracer technique, injecting SF_6 and other conserved tracers together with labeled ^{14}C-rich CO_2. Because of considerable anisotropy in the groundwater flow path at the test site, production and monitoring wells can be confidently placed downstream from the injection well. The tracers allow researchers to see the injected fluid pulse arrive at the production wells (Figure 6.9). Notably, after an initial small pulse in ^{14}C at the production well, the carbon concentration and the proportion of ^{14}C in carbon returned to near-ambient levels, indicating nearly complete loss of carbon along the approximate 100 m flow path from injection to production well. It is inferred that this carbon is lost via reaction of the injected fluid with host basalt to form carbonate minerals.

CarbFix Phase II is continuing with the methodology of Phase I, but with a deeper and wider range of injection depths (~1,500 meters at higher temperature) and a large increase in CO_2 flux. Cumulatively, more than 20,000 tons of CO_2 have been injected, with tracer results continuing to indicate nearly complete loss of carbon along an approximate 2,000 m flow path. Phase II is close to the target scale for routine operation, accommodating most of Reykjavik Energy's CO_2 emissions at a specific geothermal power plant, and also disposing of hydrogen sulfide produced at the power plant.

A rough calculation of the volume of rock infused with injected CO_2-rich aqueous fluid can be made if we assume that most of the flow is confined to a vertical interval of 10-100 m, over a width of 100 m over the flow path of 100-2,000 m in Phase I

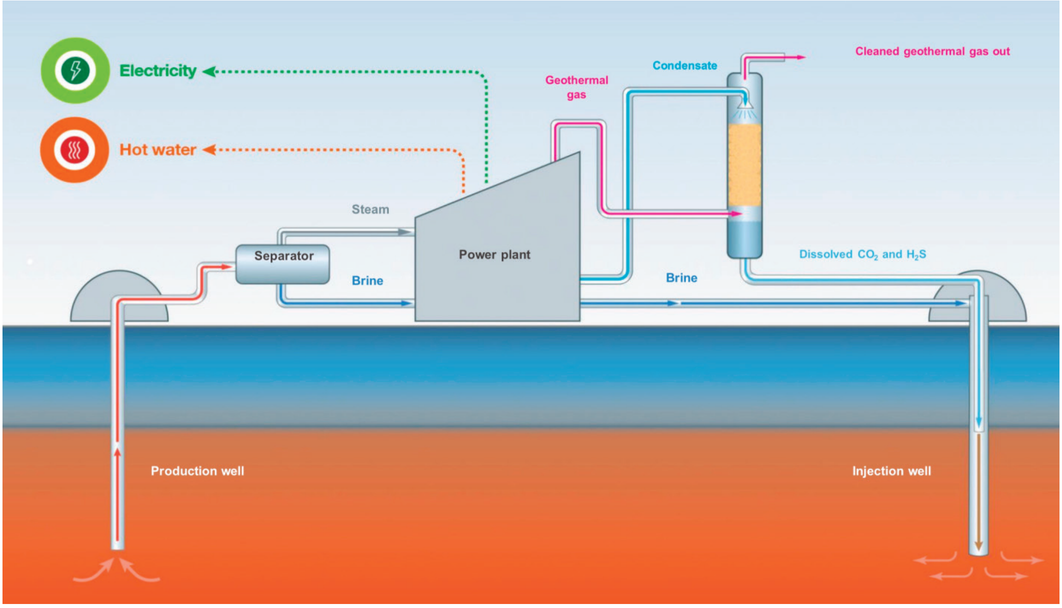


FIGURE 6.8 Schematic diagram showing flow of water and gas through the geothermal power plant at the CarbFix site.

NOTES: CO_2 and SO_2 are important constituents of the geothermal gas that are separated from other gas constituents and co-injected with geothermal brine effluent from the power plant. CO_2 + SO_2 are injected as a separate gas phase, until they are mixed with aqueous brine at a depth in proportions such that all gases dissolve in water.

SOURCE: Aradóttir, personal communication (2017).

and Phase II. (The actual volume probably widens from injection well to production well, but for this calculation we hold the width constant.) Given this assumption, the infused rock volume is about 10^5 to 2 10^7 m^3, with a density of about 2.8 t/m^3, yielding ≤ 56 Mt of rock in the Phase II injection volume. For Phase II, then, the mass fraction of CO_2 within this volume is approximately 3.6 10^{-4} (~0.7 wt% carbonate minerals) and the CO_2 uptake rate to date, in mass fraction per second, has been approximately 10^{-11}/s over 3 years. This figure corresponds to approximately 5 10^{-9} mol/m^2/s if the rock reactants can be approximated as cubes or spheres 1 mm in size. This rate is similar to those calculated using experimental data on plagioclase feldspar dissolution (Figure 6.2C) and experimental rates for full basalt carbonation (Figure 6.2B). It is possible that the initial grain size of the most reactive minerals is less than 1 mm and/or that the surface area per grain is larger than it is for cubes or spheres. If so, the rate of CO_2 consumption in the CarbFix experiment may be limited by CO_2 supply, rather than the local reaction rate, and could be substantially higher if CO_2 were injected more rapidly.

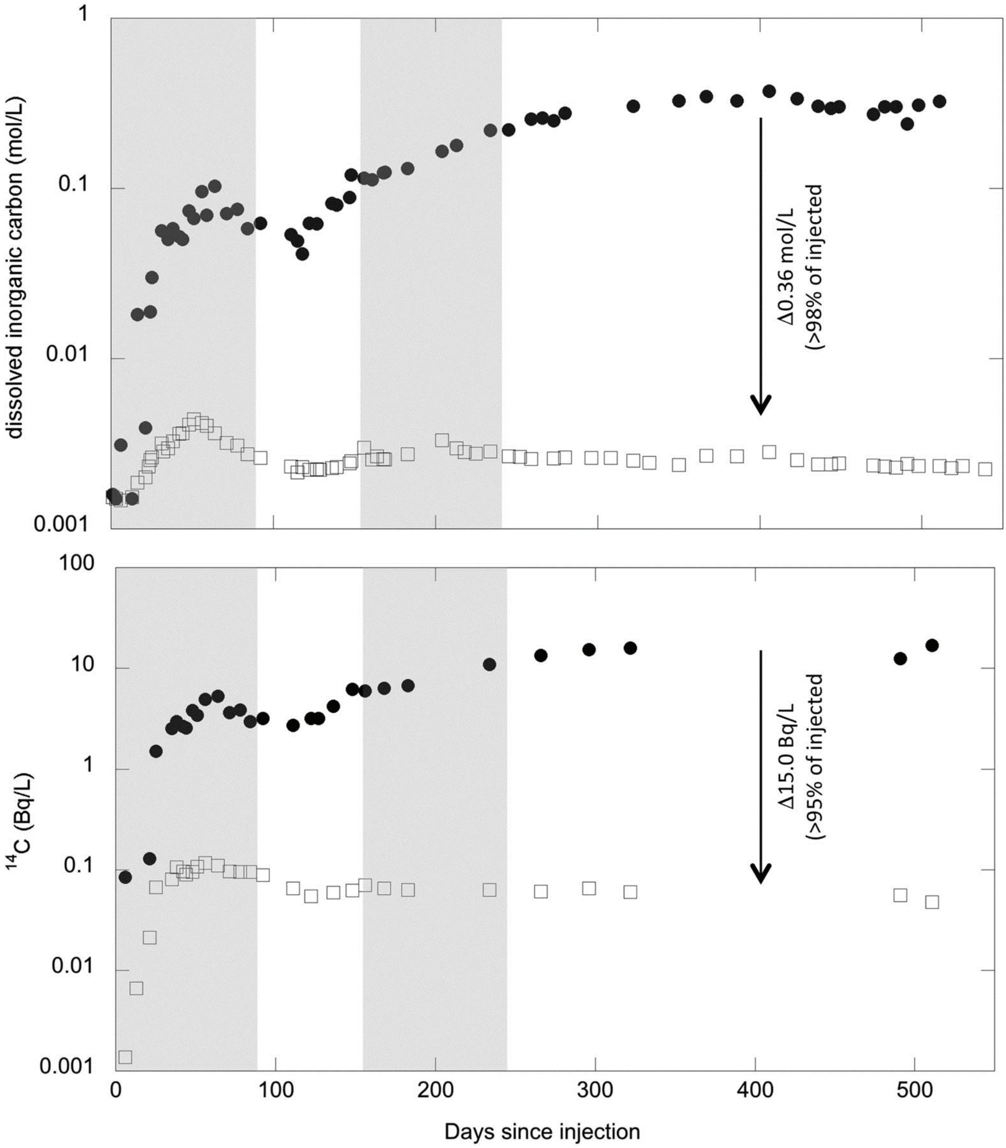


FIGURE 6.9 Predicted concentration and isotope ratio of carbon in water at the CarbFix Phase I production well, based on observed concentration of conservative tracers such as SF_6.

NOTE: The observed deficit in carbon concentration and ^{14}C are consistent with loss of consumption of almost all injected CO_2 along the flow path to form solid carbonate minerals.

SOURCE: Matter et al., 2016.

On the horizon, four concerns emerge. The first is to determine which minerals are reacting. A large variety of alteration minerals are present in Icelandic and Columbia River basalts, including zeolites, clays, and other fine-grained materials that may react rapidly. Often, such alteration phases comprise just a few percent of basaltic lavas. If alteration minerals are significant reactants in carbon mineralization, it will be important to determine their abundance to predict the capacity of the basalt reservoir at the current reaction rates. Alternatively, perhaps igneous, rock-forming minerals are the main solid reactants in carbon mineralization. This would be good news, because rock-forming minerals are probably more abundant than alteration minerals in the injection horizon.

A second concern is the possibility of passivation of reactive mineral surfaces over time, either by incongruent mineral dissolution leaving SiO_2-rich residual crusts, or by precipitation of newly formed, solid reaction products that armor the surface of solid reactants. As noted above, passivation has been observed in experiments on full carbonation of basalt and plagioclase feldspar (e.g., Gadikota et al., 2018). Basalt formations may be more susceptible to armoring of reactive surfaces with new reaction products than peridotite formations.

A third concern is clogging of pore space. To date there has been no observed reduction of permeability in the CarbFix storage reservoir (Aradóttir, personal communication, 2017). And if the small proportion of carbonate produced is widely distributed over a large fraction of the reservoir volume, one would not expect to see an appreciable change. For highly localized precipitation fronts, higher injection rates, and/or injection over longer times, permeability changes could become appreciable. However, clogging of pore space in basaltic formations, which have initial porosity of approximately 10 percent, is likely to be less important than clogging in peridotite, which have approximately 1 percent fracture-dominated porosity.

A fourth concern—or interesting variable—is the spatial distribution of carbonate mineral precipitation vs dissolution. After solution trapping at depth, the injected fluid at CarbFix has a low pH (~ 3) and is undersaturated in carbonate minerals. At low fluid to rock ratios, far from the injection site, pH will increase due to reaction with host basalt and newly formed carbonate minerals along the flow path. There must be an annulus around the injection site where existing carbonate minerals dissolve in low pH fluid and new carbonate will not precipitate. As the fluid to rock ratio increases around the injection well over time, this low pH annulus is likely to grow, with a widening volume of dissolution of newly formed carbonate pushing the zone of new carbonate precipitation outward, as predicted via modeling by Aradóttir et al., 2012.

The topics discussed in the previous four paragraphs can be examined to some extent and by forward models (e.g., Snæbjörnsdóttir et al., 2017). In addition, the actual evolution of dissolution and crystallization fronts depends on many variables whose values are poorly known. Models will need to be calibrated and validated using extensive observations. Fortunately, CarbFix Phase II is predicted to continue for several more years, and Reykjavik Energy hopes to make CO_2 (+ hydrogen sulfide) injection a standard part of its operating procedure. Note that CarbFix was not envisioned as part of a process to remove CO_2 from air, but instead as a means to store emissions from a geothermal power plant. However, recent addition of a ClimeWorks direct air capture unit at the CarbFix site serves as a concrete reminder that direct air capture systems, together with in situ carbon mineralization in basaltic lavas, could be a potent combination to achieve negative emissions.

The CarbFix methodology can be seen as a two-stage storage technique, first trapping CO_2 dissolved in water at depth, and then converting the dissolved CO_2 to solid carbonate minerals over the time groundwater flows over 2,000 m. If necessary, carbon-depleted water could be produced downstream and recycled, reducing overall water consumption. Because of the first step (solution-trapping), there is no requirement for an impermeable caprock to avoid CO_2 leakage. With an estimated cost of \$30/t (Aradóttir, personal communication, 2017) for nth-of-a-kind methods of this type, this process costs approximately \$10-20/tCO_2 more than the estimated cost of injection into subsurface pore space and could be a locally preferred option in some regions. This prospect opens vast expanses of volcanic provinces, on land and in submarine, near-shore environments, as potential storage reservoirs (Figure 6.10).

Looking more generally at the global potential for in situ carbon mineralization in basalt formations, Tables 6.1 and 6.2 indicate that both cost and tonnage are favorable for this approach, which could potentially accommodate tens of gigatons of CO_2 per year for decades. It is important to realize that basaltic lava formations—at depths of approximately less than 1,000 m, with moderately high porosity (~ 10%), and with an impermeable cap rock—can be considered appropriate reservoirs for storage of supercritical CO_2 in subsurface pore space. This approach has the added benefit that at least some of the stored CO_2 will be converted to carbonate within a few years or decades, reducing the risk of leakage and the need for monitoring as time goes by. Such hybrid methods, combining storage in pore space and relatively rapid carbon mineralization, may represent the best mix for CO_2 storage in regions with appropriate geology, as emphasized in a series of papers on onshore and near-shore marine basalt formations by Goldberg and co-workers (Goldberg and Slagle, 2009; Goldberg et al., 2008, 2010).

There has been little focus on in situ mineral capture and storage of CO_2 in basalt formations. This is due to relatively slow laboratory rates of carbon mineralization in

FIGURE 6.10 Basalt formations at and near the surface in the United States.
NOTES: In addition to the resources depicted here, there are large, onland and near-shore basalt provinces on all continents and many ocean islands. Table 6.1 lists the potential size of the basalt reservoir at 10^5 to 10^6 Gt of rock, with a potential to contain up to 25% CO_2, based on estimates from McGrail et al. (2017a) for the capacity of the Columbia River and Deccan Trapps flood basalts, extended to include other large basalt provinces onland (Parana, Siberia, North Atlantic) and near shore (Kerguelen, Iceland). We are not aware of more detailed, comprehensive reviews of the global CO_2 storage capacity of onland basalts. Goldberg and Slagle (2009) estimate the global carbon storage capacity of seafloor basalts. Modified from https://www.netl.doe.gov/coal/carbon-storage/faqs/carbon-storage-faqs#types (accessed January 28, 2019).

basalt and minerals common in basalt (particularly plagioclase feldspar) compared to ultramafic rocks and their common minerals (e.g., olivine, asbestiform chrysotile, and brucite; Figures 6.2 and 6.3). However, the potential for rapid carbon mineralization in basaltic glass (Figure 6.2C) should not be overlooked.

In Situ Carbon Mineralization in Peridotite and Other Ultramafic Rock Formations

The classic paper of Barnes and O'Neil (1969) demonstrated that mantle peridotite near Earth's surface undergoes low temperature hydration (serpentinization) and carbonation at appreciable rates. The best-studied natural example of this process is the

TABLE 6.2 Capture of CO_2 from Air and Surface Waters Plus Solid Storage, via Carbon Mineralization at Ambient $P(CO_2)$ and Temperature

	Location	Method	Grain size and crack spacing microns	Natural rate t/y CO_2	Rate weight fraction CO_2/y	Rate t CO_2/km³/y	CO_2 reservoir production Gt rock/y	CO_2 reservoir Gt rock	Max CO_2 weight fraction at rate in table	Cost $/t CO_2	References	Notes
Natural processes												
Mine tailings rich in brucite and fine chrysotile	Mt. Keith Mine, AU	Natural percolation	20-200	4.0E+04	3.6E-03	9.0E+06		0.011	0.03-0.1	0	Wilson et al., 2014	1, 2
Mine tailings rich in brucite and fine chrysotile	Diavik Mine, CA	Natural percolation	20-200	3.0E+04	4.0E-05	1.6E+04		0.002	0.03-0.1	0	Wilson et al., 2011	1, 2, 3
Serpentinite mine tailings	Black Lake Mine, CA	Natural percolation	20-200	6.0E+03	5.0E-05	2.0E+04		0.120	0.03-0.1	0	Pronost et al., 2012	1, 2
Global ultramafic mine tailings	Global	Natural percolation	20-200				0.200	<10	0.03-0.1	0	Dipple and Kelemen, personal communication, 2017	
Fractured peridotite aquifers	Oman, depth <3 km	Natural groundwater circulation	1–1E6		3.3E-07	1.0E+03		50,000	0.60	0	Kelemen and Matter, 2008	4, 5, 6

continued

TABLE 6.2 Continued

	Location	Method	Grain size and crack spacing microns	Natural rate t/y CO_2	Rate weight fraction CO_2/y	Rate t CO_2/km^3/y	CO_2 reservoir production Gt rock/y	CO_2 reservoir Gt rock	Max CO_2 weight fraction at rate in table	Cost $/t CO_2	References	Notes
Global fractured peridotite aquifers	On land, depth below surface <3 km	Natural groundwater circulation	2–1E6		3.3E-07	1.0E+03		1E5-1E6	0.60	0	Kelemen et al., 2011	4, 5, 6
Global fractured peridotite aquifers	Seafloor, depth below seafloor <3 km	Natural groundwater circulation	3–1E6		3.3E-07	1.0E+03		~1E8	0.60	0	Kelemen et al., 2011	4, 5, 6
Soils contaminated with Ca-rich building waste	Newcastle, UK	Natural percolation	1-100		4.6E-03	9.2E+06			~ 0.015	0	Manning and Renforth, 2013; Renforth et al., 2009; Washbourne et al., 2015	3, 7
Enhanced processes												
Nearly pure $Mg(OH)_2$ from brucite mine	Lab experiment	Air sparged through brucite + H_2O	2-40		9.9E-05	2.5E+05	0.200	<10	0.03-0.1	10-30	Harrison et al., 2013	1

Bioleaching and microbial carbonate precipitation	Proposed	Bioengineered		3.6E-3–3.6E-2		0.200	<10	0.03-0.1	10-30	Power et al., 2010, 2011, 2013a	7
Thinner distribution, stirring of ultramafic mine tailings	Generic	Mechanical		3.6E-3–3.6E-2		0.200	<10	0.03-0.1		Assima et al., 2013a; Harrison et al., 2013; Power et al., 2013c; Wilson et al., 2014	7
Ground peridotite or basalt on soils, beaches	Lab experiment	Grinding and broadcast	0.01-1.0	5E-11–5E-10	0.025-0.25		28,000	0.05?	25-115	Hartmann et al., 2013; Köhler et al., 2013; Montserrat et al., 2017; Renforth, 2012; Renforth et al., 2015; Rigopoulos et al., 2018	3, 8-11

continued

TABLE 6.2 Continued

	Location	Method	Grain size and crack spacing microns	Natural rate t/y CO_2	Rate weight fraction CO_2/y	Rate t CO_2/ km^3/y	CO_2 reservoir production Gt rock/y	CO_2 reservoir Gt rock	Max CO_2 weight fraction at rate in table	Cost \$/t CO_2	References	Notes
Produce alkaline water from peridotite aquifers	Generic	Drill, pump if necessary	NA							~10?	Kelemen et al., 2016	5, 12, 13
Circulate water through high permeability peridotite aquifers via thermal convection	Generic	Drill to depth where temp ~90°C, flow and recharge driven by hydrothermal convection, permeability 10-12 m^2	1–1E6		1.5E-4–1.5E-3	4.5E5–4.5E6		1E5-1E8	0.60	30-60	Kelemen et al., 2011, 2016	5, 14
Circulate water through low permeability peridotite aquifers via pumping	Too costly	Drill to depth where temp ~ 90°C, flow and recharge driven by pumping, permeability 10–14 m^2	1–1E6		1.5E-4–1.5E-3	4.5E5–4.5E6		1E5-1E8	0.60	3,000-6,000	Kelemen et al., 2016	5, 11, 14

Circulate water through peridotite aquifers combined with geothermal power generation	Generic	Reduce cost of geothermal power generation via carbon offsets	1–1E6	1.5E-4–1.5E-3	4.5E5–4.5E6		0.60	<0?	Kelemen et al., 2011, 2016	5, 14
Mine ultramafic rock to create tailings for carbon removal	Generic	Mining and grinding	20–200			1E5–1E6	0.03–0.1	100–300	Dipple and Kelemen, personal communication, 2017	15
Artificial mix of organic waste and quarry fines	Lab experiment	Natural percolation	2–3400	8.81E-04	1.76E+06	2E4–5E4	~ 0.015	50–100?	Manning and Renforth, 2013; Renforth et al., 2009; Washbourne et al., 2015	3, 8, 9

NOTES

1. Assumed density of tailings 2.5 t/m^3.
2. Impacts may be confined to mine tailings sites, assumed density of tailings 2.5 t/m^3.
3. Assumed depth of carbonation in tailings and soil 1 m.
4. Assumed density of partially serpentinized natural peridotite 3 t/m^3.
5. No known geochemical contamination; water from peridotite-hosted aquifers is within EPA safe drinking water limits.
6. Rates of natural CO_2 uptake tabulated here may be confined to upper 15 m, but reservoir size tabulated here is upper 3 km.

continued

TABLE 6.2 Continued

7. Maximum of 10× acceleration compared to fastest known natural rate.

8. Assumed density of soil 2 t/m^3.

9. Total mass is global area of arable soil to depth in (3).

10. Ni and Cr may accumulate in soils over time.

11. $10 to mine and grind to tailings size, 300 to 350 kWh/ton CO_2 to mill from tailings to 1 micron, assumed cost of energy $0.05 to 0.30/kWh.

12. If drilled at existing spring sites, pumping should be minimal, cost is simply cost of typical water well.

13. Once calcite is precipitated and water reaches normal pH, discharge to local drainages.

14. Crystallization of carbonate minerals in subsurface could destroy permeability and armor reactive surfaces, or alternatively could maintain or enhance permeability and reactive surface area via reaction-driven cracking (Jamtveit et al., 2008; Kelemen and Hirth, 2012; MacDonald and Fyfe, 1985; Zhu et al., 2016).

15. $10 per ton of rock for mining and grinding to typical tailings size.

alteration of mantle peridotite in the Samail ophiolite (e.g., Neal and Stanger, 1985), a block of oceanic crust and mantle peridotite thrust onto the Arabian continental margin from 96 to 70 million years ago, and now exposed by faulting and erosion in northern Oman and the eastern United Arab Emirates. Present-day carbon mineralization forms carbonate veins in fractures, within partially serpentinized peridotites at ambient, near-surface temperature and pressure, and large travertine terraces of chemically deposited calcite ($CaCO_3$) on the surface. Ongoing rates of carbonation, constrained by ^{14}C geochronology and other data, are about 1 gm $CO_2/m^3/y$ (1,000 t/km^3/y) in a weathering horizon that may have an average depth of approximately 15 m (Kelemen and Matter, 2008; Kelemen et al., 2011; Mervine et al., 2014; Streit et al., 2012). Carbonates in the rock matrix and in veins filling fractures constitute about 1 percent of peridotite in outcrop, on average. In the past, fully carbonated peridotites, known as listvenites, in which all Mg and Ca have combined with CO_2 to form carbonate minerals, and SiO_2 is present as quartz, formed in Oman at somewhat higher temperature, approximately 100°C, in the presence of fluids with high $P(CO_2)$ (de Obeso et al., 2017; Falk and Kelemen, 2015; Godard et al., 2017; Kelemen et al., 2017; Manning et al., 2017), similar to conditions for proposed *in situ* CO_2 storage.

Research on engineered in situ carbon mineralization in peridotite is motivated by five key factors. First, the mineral olivine is the most abundant mineral in Earth's upper mantle and remains abundant in most partially altered peridotites that have been exposed at and near the surface. At conditions accessible in the upper few km of Earth's crust (temperatures from 50 to 300°C, and/or elevated $P(CO_2)$), olivine reacts with CO_2 in fluids to form solid carbonate minerals faster than any other common, rock-forming silicate mineral (see "Carbon Mineralization Kinetics"). In altered peridotites at low temperatures, the mineral brucite also reacts rapidly with CO_2 to form solid carbonates. Olivine and brucite undergo rapid carbonation because their solubility in aqueous fluids is moderately high, and intra-mineral diffusion is relatively fast, compared to rock-forming alumino-silicate minerals such as plagioclase feldspars, which are abundant in basalt.

Second, high solubilities and rapid reaction rates for carbon mineralization in olivine and other minerals in mantle peridotite are due, in part, to the fact that they are far from CO_2, H_2O, and O_2 exchange equilibrium with air and surface waters. Where mantle peridotite massifs are exhumed, they constitute an immense reservoir of chemical potential energy that drives rapid, spontaneous reaction and can be converted into both heat (Kelemen and Matter, 2008) and work (Kelemen and Hirth, 2012). Engineered systems that utilize this potential energy could, in principle, be among the least expensive routes to combined CO_2 capture from air and solid storage. Proposed methods for engineered carbon mineralization in peridotite involve emulating natural systems to harness this chemical potential to minimize external energy inputs and costs.

Third, as reviewed by Kelemen et al. (2011) and Kelemen and Manning (2015), carbonate veins are abundant in outcrops of mantle peridotite (Figure 6.11). Peridotite outcrops worldwide are also hosts to alkaline springs, rich in dissolved $CaOH^-$, with little dissolved Mg and C (e.g., Barnes and O'Neil, 1969, 1971; Barnes et al., 1967, 1978; Clark and Fontes, 1990; Falk et al., 2016; Kelley et al., 2001; Launay and Fontes, 1985; Mervine et al., 2014; Neal and Stanger, 1985). Alkaline spring waters are interpreted as products of precipitation of Mg-carbonate minerals during reaction of groundwater with peridotite, together with dissolution of Ca-bearing silicates in peridotite (e.g., pyroxenes and plagioclase). At the surface, alkaline spring water combines directly with CO_2 from air to form calcium carbonate ($CaCO_3$) in locally extensive travertine terraces (Figure 6.12). ^{14}C data indicate that most of these large travertine deposits form in less than 20,000 years (Kelemen and Matter, 2008; Kelemen et al., 2011; Mervine et al., 2014; Streit et al., 2012).

FIGURE 6.11 White carbonate veins in partially serpentinized peridotite in Oman. These veins formed by precipitation in fractures plus diffusive exchange with surrounding wall rocks.
SOURCES: Two lefthand images from Kelemen, personal communication, 2017. Top right: Kelemen and Matter, 2008. Bottom right: Falk and Kelemen, 2015.

Fourth, fully carbonated peridotites (listvenites), in which all Mg has combined with CO_2 to form carbonate minerals, while Si remains in pure SiO_2 minerals (quartz, chalcedony, and/or opal), are exposed in Oman (Falk and Kelemen, 2015; Lacinska et al., 2014; Nasir et al., 2007; Stanger, 1985; Wilde et al., 2002) and elsewhere around the world (e.g., Akbulut et al., 2006; Beinlich et al., 2012, 2014; Boschi et al., 2009; Garcia del Real et al., 2016; Halls and Zhao, 1995; Hansen et al., 2005; Quesnel et al., 2013, 2016; Tominaga et al., 2017; Ulrich et al., 2014). Figure 6.13 illustrates listvenites in Oman. Many of these record replacement at ~ 100°C, within the temperature range where carbon mineralization rates are high. The presence of listvenites reveals that there are natural pathways to complete reaction under such temperature conditions, despite potential negative feedbacks discussed in the "Feedbacks between reaction and fluid flow during in situ carbon mineralization" section.

Fifth, when fully carbonated, initially olivine-rich peridotite (dunite) can incorporate 40 wt% CO_2—a 60 percent increase in solid mass, relative to the initial mass of olivine. For example, iron-free olivine (Mg_2SiO_4, ~ 41 gm/mol) + 2 CO_2 (2 × 44 gm/mol) forms two moles of magnesium carbonate ($MgCO_3$) plus one mole of quartz (SiO_2). This, combined with the abundance of peridotite within 3 km of Earth's surface, yields storage reservoirs capable in principle of holding 10^5 to 10^8 Gt CO_2 in solid form (Kelemen et al., 2011, 2016; Tables 6.1 and 6.2).

FIGURE 6.12 Travertine deposits composed of calcite formed by reaction of atmospheric CO_2 with carbon-free, alkaline spring water rich in $CaOH^-$ from a peridotite aquifer in Oman.
SOURCE: Images from Kelemen and Matter, 2008.

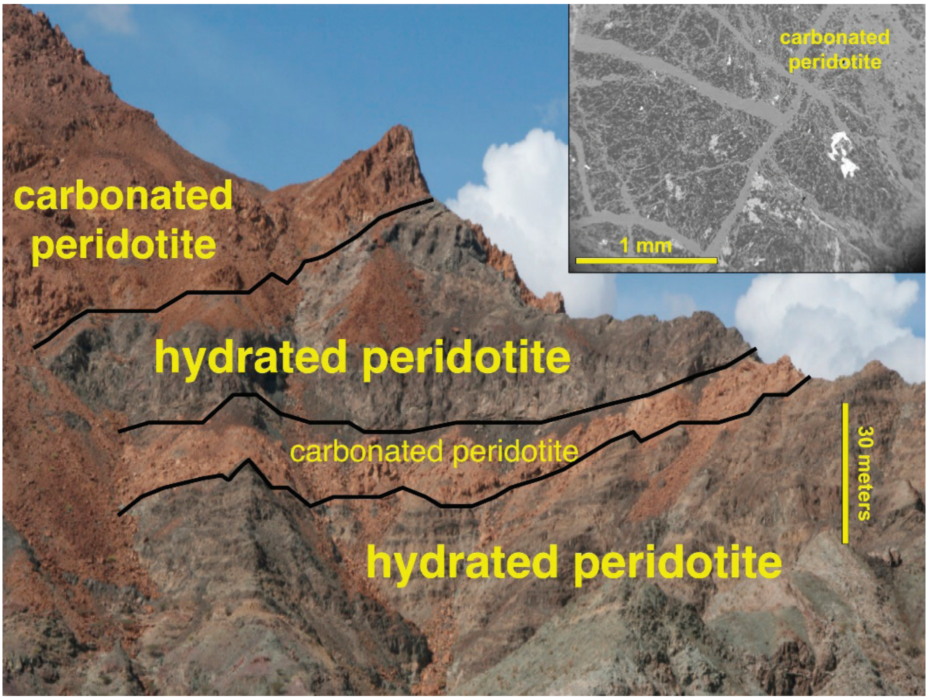


FIGURE 6.13 Red bands of fully carbonated peridotite (listvenite) in green-grey partially serpentinized mantle peridotite in Oman.
NOTE: Inset is a back-scattered electron image of listvenite, in which dark grey areas are magnetite, light grey areas are quartz, and bright grey and white areas are Cr-rich oxide minerals.
SOURCE: Images from Falk and Kelemen, 2015.

The combination of these five factors has sustained basic research on natural and engineered in situ carbon mineralization in peridotite massifs for a decade. However, there have been no field-scale investigations of engineered, in situ carbonation of peridotite. This may be due to several factors, including the lower initial porosity and permeability of peridotite relative to basalt, the lower abundance of peridotite outcrops, and their location far from population centers and point-source CO_2 emitters. As a result of this lack of experience, assessment of the potential pros and cons of in situ mineral carbonation in peridotite remains highly speculative, a topic for basic research and initial engineering assessment.

Feedbacks between reaction and fluid flow during in situ carbon mineralization

In natural and engineered systems, rapid and extensive carbon mineralization could be inhibited by negative feedback processes. Loss of CO_2 by reaction along the initial stages of a reactive fluid pathway could limit supply of CO_2 to rocks more distal from an injection well. Filling of pore space with reaction products may reduce permeability and armor reactive surfaces, forming a solid diffusive boundary layer between fluid and solid reactants. These negative feedbacks may commonly cause peridotite carbonation (and hydration and oxidation) to be self-limiting, preserving lithologies in outcrop that are far from equilibrium with surface conditions.

The reactions outlined in the Introduction all involve large increases in the solid volume, via addition of CO_2 (± H_2O, ± O_2) from the fluid into the solid phases coupled with the low density of solid products relative to solid reactants. If large volumes of other components were dissolved from the rock volume, then perhaps the net change in solid volume change would be small. However, we infer from nearly constant ratios of major cations (Mg/Si, Mg/Fe) in fully carbonated peridotites, compared to CO_2-free peridotite reactants that there has been very little dissolution and transport of material out of the rock system (Kelemen et al., 2017), consistent with decades of prior studies (e.g., Coleman and Keith, 1971; Malvoisin, 2015). Near-surface peridotites have fracture-dominated porosity of approximately 1 volume percent. Small increases in the solid volume and precipitation of minerals in pore space, in such a limited porosity network, could have large, negative impacts on permeability, potentially limiting carbon mineralization in peridotite reacting with CO_2-rich fluids.[2]

Nevertheless, natural alkaline springs, formed as a result of subsurface peridotite carbonation and hydration, persist for 10s of thousands to 100s of thousands of years (Früh-Green et al., 2003; Kelemen and Matter, 2008; Kelemen et al., 2011; Ludwig et al., 2006; 2011; Mervine et al., 2014, 2015), indicating that the underlying reactive flow network does not clog or exhaust reactive surface area on this timescale. In addition, observations summarized in the first few paragraphs of this section indicate that complete carbonation, in which all Mg- and Ca-cations combine with CO_2, does occur.

A positive feedback mechanism that may explain the persistence of geologically rapid peridotite carbonation, extending over long times and continuing to 100 percent completion, is reaction-driven cracking in which volume expansion due to

---

[2] The negative feedbacks outlined above are most likely during subsurface carbon mineralization in peridotite using CO_2-rich fluid reactants for CO_2 storage. In contrast, clogging of porosity may be less important for slow uptake of CO_2 from circulating surface waters, in methods for CO_2 removal from air and solid storage.

carbonation causes large differential stresses, which in turn cause fractures, maintaining or enhancing permeability and reactive surface area (Figure 6.14; Jamtveit et al., 2008; 2009; Kelemen and Hirth, 2012; MacDonald and Fyfe, 1985; O'Hanley, 1992; Rudge et al., 2010; Ulven et al., 2014a, 2014b; Zhu et al., 2016). In experiments on olivine powder, as noted above, the lack of passivation (Figure 6.3) may be a very small-scale result of the reaction-driven cracking process, in which observed layers of amorphous SiO_2 on olivine surfaces (Béarat et al., 2006; Chizmeshya et al., 2007) fracture and spall off dissolving grains, or are "pushed" from the surface by precipitating reaction products. Available chemical potential energy to drive reaction-driven

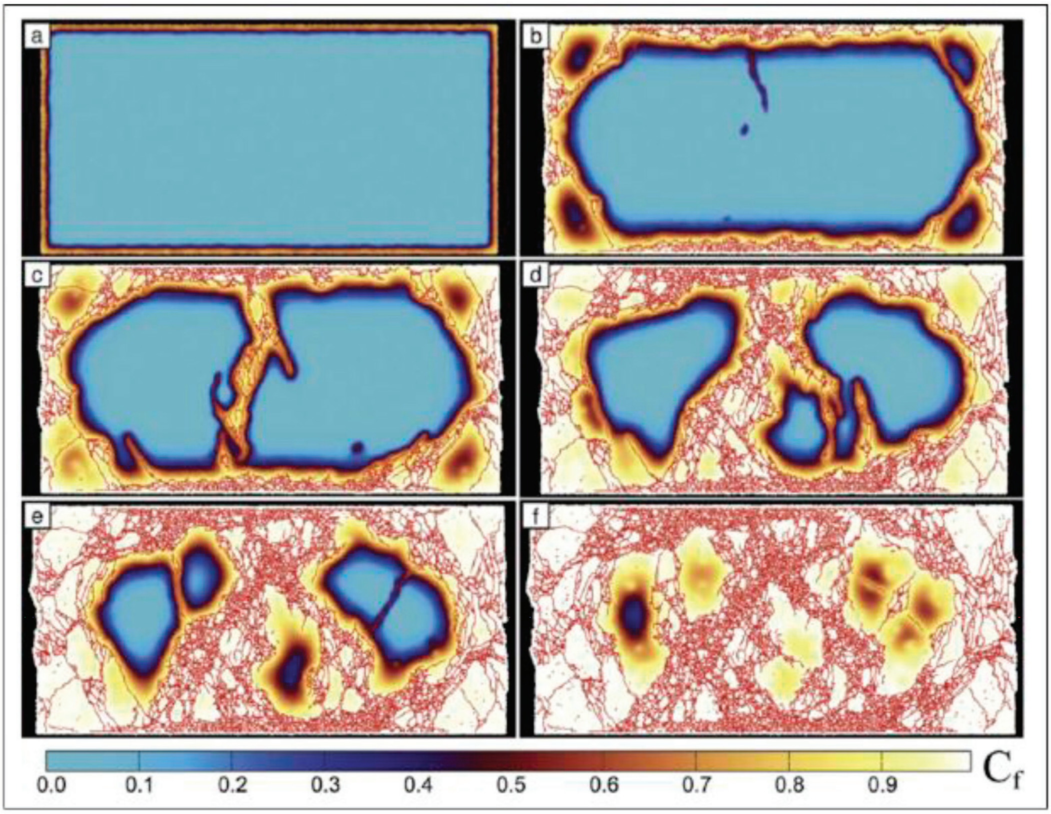


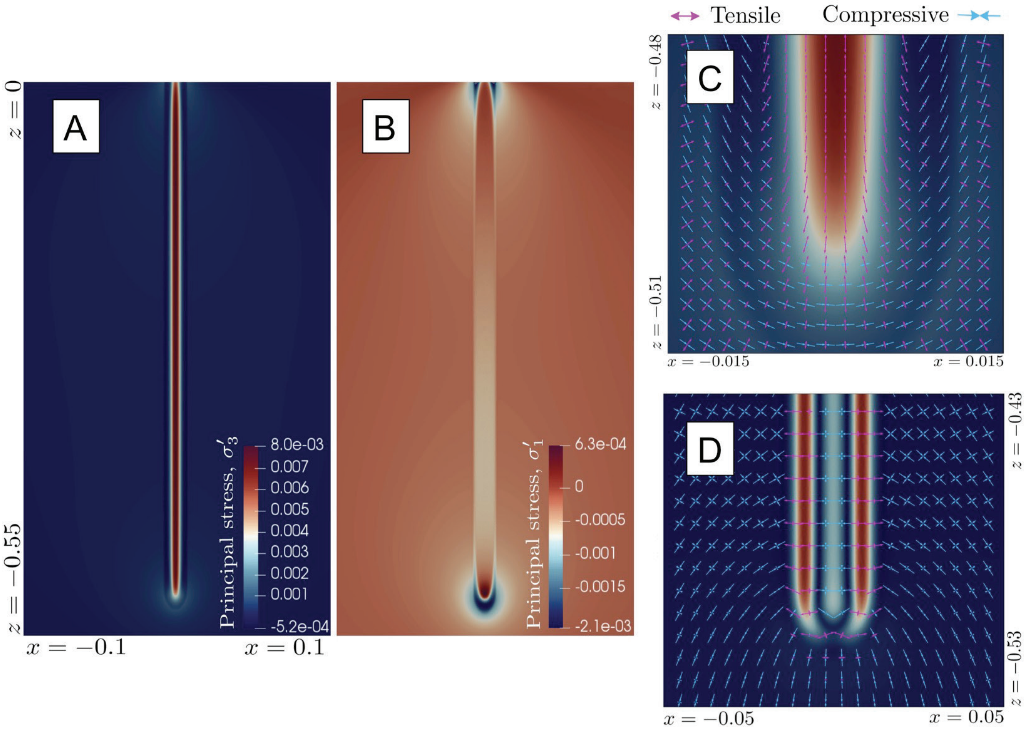
FIGURE 6.14 Numerical model of reaction driven cracking (Røyne et al., 2008) in a rectangular block of rock surrounded by fluid in two dimensions.
NOTES: Blue rock reacts with black fluid to form white solid products, with volume increase and associated stress concentrations forming red cracks. In turn, cracks provide rapid fluid access deeper into the rock. This discrete element model provides clear simulations of fracture formation at the grain scale, but does not incorporate Darcy flow within the porous fracture network.

cracking in peridotite undergoing carbonation or hydration is large, more than sufficient to fracture rocks (Kelemen and Hirth, 2012). The overall concept seems simple enough, and this process has been observed in peridotite carbonation experiments (Zhu et al., 2016).

Nevertheless, in other experimental tests of olivine carbonation and hydration, volume change and fractures were not observed (van Noort et al., 2017), and permeability dropped with increasing reaction progress (Andreani et al., 2009; Godard et al., 2013; Hövelmann et al., 2012). The reasons for this are not yet clear. It is becoming apparent that micro- and nano-scale properties of fluid-rock systems, such as fluid-mineral surface energy, and related characteristics such as sorptivity and disjoining pressure (Evans et al., 2018; Lambart et al., 2018; Zheng et al., 2018) may play a significant role in locating the crucial bifurcation between self-limiting negative feedbacks (clogging) and accelerating, positive feedbacks (cracking) (Figures 6.15 and 6.16). In addition, viscous and/or frictional dissipation of stress, for example in weak reaction products such as gypsum (Skarbek et al., 2018) and brucite (Moore and Lockner, 2004, 2007; Morrow et al., 2000; Zheng et al., 2018), may also reduce crystallization pressure before stresses due to volume expansion become high enough to generate new fractures.

Other processes—such as selective, local dissolution and precipitation processes (Lisabeth et al., 2017; Peuble et al., 2018) and/or crack propagation from etch pits along dislocation boundaries and other defects in olivine crystals (Daval et al., 2011; Grozeva et al., 2017; Klein et al., 2015; Lisabeth et al., 2017; Malvoisin et al., 2017; McCollom et al., 2016; Plümper et al., 2012; Rouméjon and Cannat, 2014; Velbel, 2009)—may also play a role in sustaining permeability and fluid flow. Perhaps complete carbonation in natural systems is relatively slow, and thus cannot be engineered on a human time scale, as suggested by van Noort et al. (2017). However, in the competition between (1) volume expansion and stress accumulation and (2) processes that relax elastic stresses such as viscous flow or frictional sliding along existing fractures, it seems likely that reaction-driven cracking happens when the rates of reaction and volume change are maximized.

In summary, despite the initial, apparent simplicity of the feedbacks in peridotite carbonation, understanding them and developing predictive hypotheses validated by experimental and field observations is an increasingly complex and interesting research field. And again, continued research on this topic is justified by geologic observations of fully carbonated peridotite. If natural systems can do it, it is likely to be possible to design engineered systems that emulate this process. Moreover, understanding of the feedbacks that lead to reaction-driven cracking could be applied to geothermal power generation, in situ mining for, for example, uranium, and extraction of oil and gas


Tensile
Compressive
A
B
C
D
$z = 0$
$z = -0.55$
$x = -0.1$
$x = 0.1$
Principal stress, σ'_3
8.0e-03
0.007
0.006
0.005
0.004
0.003
0.002
0.001
-5.2e-04
Principal stress, σ'_1
6.3e-04
0
-0.0005
-0.001
-0.0015
-2.1e-03
$z = -0.48$
$z = -0.51$
$x = -0.015$
$x = 0.015$
$z = -0.43$
$z = -0.53$
$x = -0.05$
$x = 0.05$

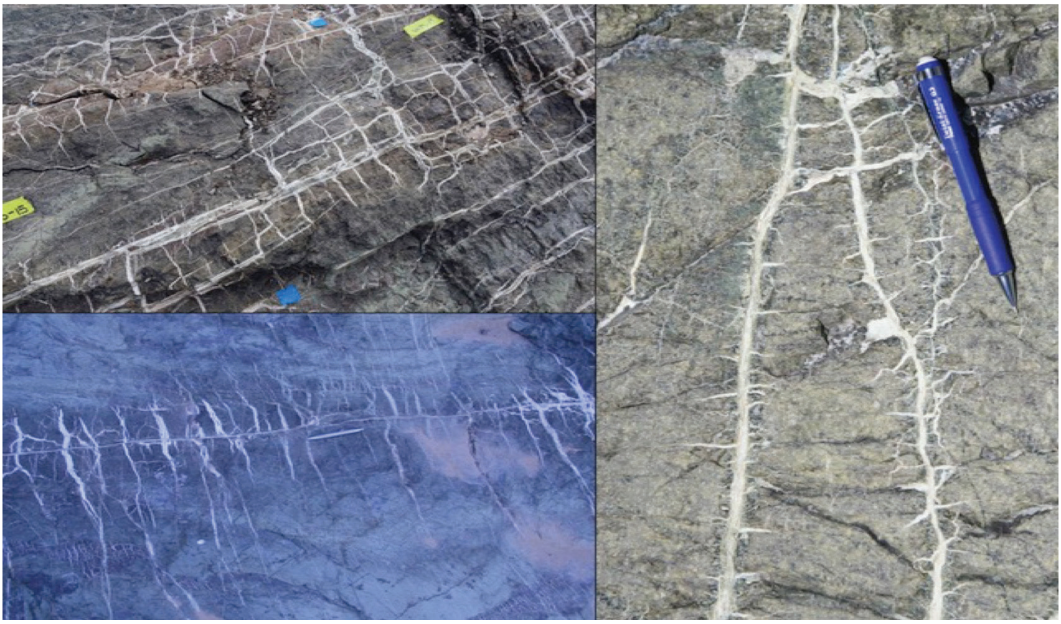


FIGURE 6.15 (Facing page) Top panels: Nondimensional stresses (colors) in 2D model of a tabular zone of high porosity infiltrated by CO_2-rich fluid, reacting with olivine to produce carbonate minerals with volume expansion. A. Model domain, showing magnitude of the least compressive principal stress around the fracture after reaction, in a model without surface energy driven "capillary" flow. Maximum tensile stress (dark red) is 80 MPa. B. Magnitude of the largest principle compressive stress, with a minimum value of 21 MPa, in a model lacking surface energy driven flow. C. Directions of maximum tensile and compressive stresses, with lengths scaled to the largest principle stresses, in a model without surface energy driven flow. D. As for C, but in a model including surface energy driven fluid flow. Bottom photos: White carbonate veins in partially serpentinized peridotite, with a characteristic texture called ladder cracks or Frankenstein veins in which a central, carbonate vein is flanked by smaller, terminated, carbonate veins perpendicular to the central one, similar to the model results in panel C.
SOURCE: Evans et al., 2018.

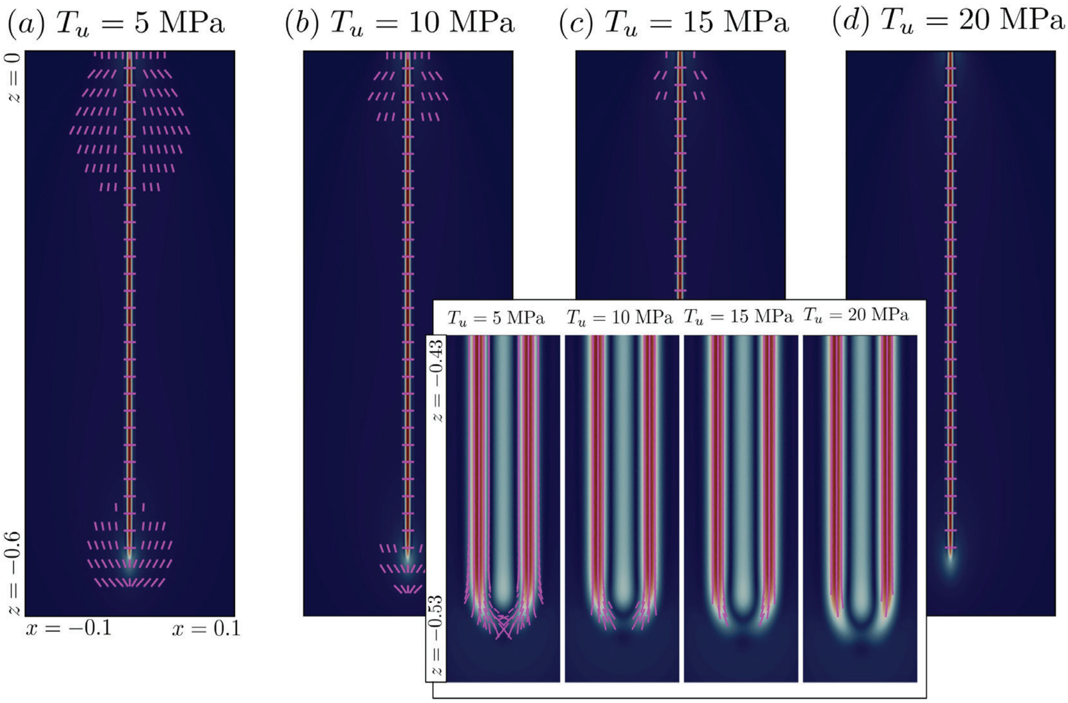


FIGURE 6.16 Pink lines indicate position and length of tensile fractures that would form in 2D model of a tabular zone of high porosity infiltrated by CO_2-rich fluid, reacting with olivine to produce carbonate minerals with volume expansion. Panels labeled (a)-(d) illustrate results of a model without surface energy driven "capillary" flow, as a function of the tensile stress required for fracture, labeled at the top of each panel. The inset illustrates results of a model including surface energy driven fluid flow.
SOURCE: Evans et al., 2018.

from tight reservoirs, as well as to CO_2 capture and storage. In other applications, it is desirable to prevent reaction-driven cracking, for example in well-bore cement and in caprocks above storage reservoirs for supercritical CO_2 fluid. Ongoing research seeks to outline a "phase diagram" delineating the conditions for reaction-driven cracking, and the surrounding parameter space dominated by clogging and armoring of reactive surfaces.

Solid storage of CO_2 via in situ carbon mineralization in peridotite

Kinetic data summarized in the "Carbon Mineralization Kinetics" section yield empirical predictions of olivine carbonation rates (mass fraction olivine ≤ 75 microns) such as:

$$\Gamma = 1.15\ 10^{-5}\ (P(CO_2)\ \text{bars})^{1/2}\ \exp[0.000334(T°C-185)^2]$$ (Kelemen and Matter, 2008; further validated in Gadikota et al., 2014)

Rather than guess the effective grain size (and/or fracture spacing) in natural peridotite aquifers, we use observed rates in the near-surface weathering horizon as a calibration point, calculate relative rate enhancements using this expression, and derive a scaled rate from the product of the observed rate and the relative rate enhancement. This approach indicates that olivine-rich peridotite could, in principle, consume more than 1 Gt CO_2/km^3 peridotite/y, at temperatures greater than approximately 150°C, and CO_2 partial pressures greater than approximately 60 bars (Kelemen and Matter, 2008). Even at somewhat lower temperatures, approximates 100°C, carbon mineralization in peridotite reacting with high $P(CO_2)$ fluids could achieve rates of 300 Mt CO_2/km^3/y. For drilling costs of \$3M to \$6M, and compression costs of \$10/t of injected fluid, over 10 years this process could lead to solid storage[3] of 3 Gt CO_2 at \$10-20/t ton. Figure 6.17 illustrates how solid storage of 3 Mt/y CO_2 might be achieved at this cost, by injecting CO_2-rich fluid into a rock volume of 10^7 m^3 (10^{-2} km^3) surrounding a single 3 km deep borehole.

CO_2 removal from air and solid storage via in situ carbon mineralization in peridotite

CO_2 removal from air, in addition to solid storage, may be achieved using engineered methods that closely emulate natural carbon mineralization in peridotite. During

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[3] Although the term "storage" might imply accumulation for future use, the committee uses this term interchangeably with the term "sequestration" in accordance with the literature reviewed.

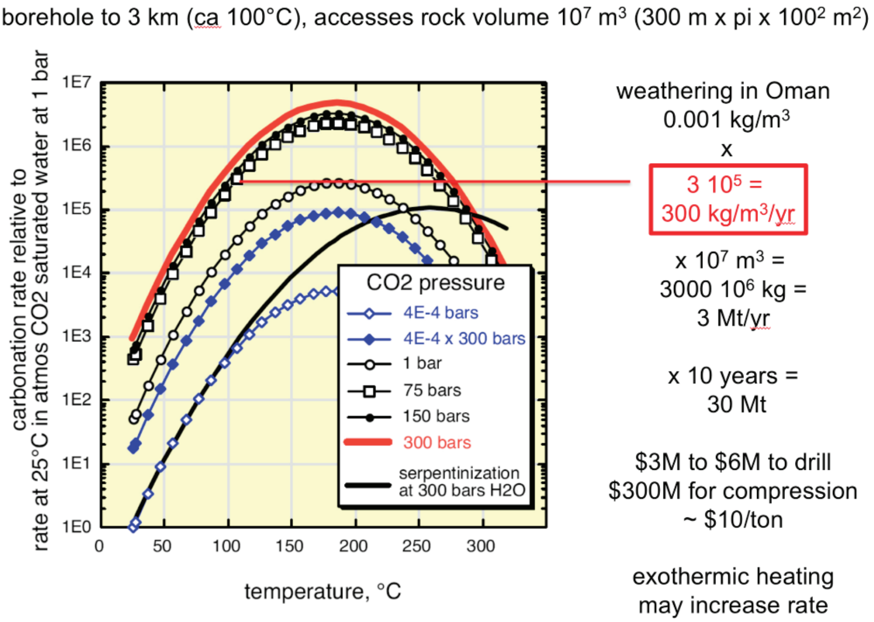

FIGURE 6.17 CO_2 uptake, via injection of fluid with $P(CO_2)$ ~70 bars into peridotite at ~100°C (surface 25°C + 3 km depth at 25°C/km), and the associated cost.
NOTES: Values of rate enhancement relative to the rate at 25°C in air, due to elevated temperature and $P(CO_2)$, are from Kelemen and Matter, 2008, fit to data of O'Connor et al., 2005, consistent with experimental data of Gadikota et al., 2014. Rate of peridotite carbonation due to weathering in Oman is from Kelemen and Matter, 2008 and Kelemen et al., 2011. Drilling costs from, e.g., Augustine et al., 2006, Bloomfield and Laney, 2005, and Shevenell, 2012. CO_2 compression costs from, e.g., McCollum and Ogden, 2006 and Rubin et al., 2015.

weathering, shallow groundwater, equilibrated with atmospheric CO_2, reacts with peridotite in the subsurface, in a system closed to CO_2 exchange with the atmosphere. This quickly reduces dissolved carbon concentrations to zero, via precipitation of Mg- and Ca-carbonate minerals in veins (Figure 6.11). Along the reaction path, pH rises to 11.5 or more, and the concentration of dissolved Ca^{2-} increases to approximately 400 ppm. When these alkaline waters reach the surface, they combine with atmospheric CO_2 to form calcite, $CaCO_3$, in some places creating extensive travertine deposits (Figure 6.12; e.g., Barnes and O'Neil, 1969; Barnes et al., 1978; Clark and Fontes, 1990; Kelley et al., 2001; Launay and Fontes, 1985; Neal and Stanger, 1985).

Engineered CO_2 removal from air could begin with production of C-depleted alkaline water from existing aquifers in peridotite, to form travertine at the surface. The amount of CO_2 that could be captured via this simple and relatively inexpensive method is uncertain, because the size, permeability, productivity and recharge rates of alkaline, peridotite-hosted aquifers are unknown. This represents an obvious, relatively low-cost research opportunity.

In parallel, alkaline aquifers could be replenished via enhanced circulation of surface water through subsurface peridotite formations. For this method, it is important to consider the cost of pumping fluid. Because of the dilute concentration of carbon-species in water equilibrated with air at 1 bar (~100 ppm CO_2), every penny spent pumping water corresponds to approximately \$100/tCO_2. Thus, it may be best to rely on thermal convection to drive fluid circulation. In this context, the temperature contrast between surface water and the target aquifer, and the permeability of the subsurface peridotite aquifer, are critical variables. Where thermal convection is sufficient to drive circulation ($\Delta T > 50°C$, permeability $> 5\ 10^{-13}\ m^2$), drilling expenses similar to those for geothermal wells, amortized over a 20-year lifespan, yield highly approximate, estimated costs of less than \$100/tCO_2 (Kelemen et al., 2016).

In lower permeability formations (permeability $< 5\ 10^{-14}\ m^2$) added costs due to the energy requirements for pumping fluid rise above \$1,000/t. Such high costs would render CO_2 capture via circulation of surface water impractical. An exception could be co-located geothermal power generation and CO_2 capture. Large geothermal power plants commonly employ pumps at the surface and within boreholes, optimizing the flow rate to generate maximum electricity at a minimum pumping rate. In this mix, carbon offsets for CO_2 capture could increase revenues directly, and/or allow additional pump pressure, more rapid fluid flow rates, and additional electrical generation.

Individual injection wells probably can capture a maximum of approximately 1,000 t$CO_{2/y}$ via carbon mineralization without significant pumping. Capturing gigatons of CO_2 is possible, simply via drilling more wells. The number of wells required to capture 1 Gt/y CO_2 in this way is approximately equal to the number of operating oil and gas wells in the United States. However, there are no obvious economies of scale that would reduce the cost of capture per ton.

Some key uncertainties require medium-scale field testing. In particular, the evolution of reaction progress and permeability during flow of fluid in a crystalline rock aquifer containing hierarchical fracture networks is difficult to predict. While modeling efforts are advisable, there really is no substitute for experiments at a scale that is tens to hundreds of times larger than the spacing of key fracture sets.

As is evident from Tables 6.1 and 6.2, the potential reservoir for CO_2 capture and storage in peridotite formations is enormous, with a capacity greater than 10^5 Gt CO_2. Both rates and costs of CO_2 capture from subsurface circulation of water saturated in air are potentially competitive with other methods to achieve CO_2 removal from air, and as a consequence proposed methods warrant intensified, basic research to delineate the conditions for cracking rather than clogging, and to determine a variety of important physical properties of fractured, partially serpentinized, subsurface peridotite. Additionally, field tests should shed light on the potential for contamination of local water supplies,[4] induced earthquakes, and other negative impacts.

If pathways can be found to positive feedback regimes—in which carbon mineralization causes small-scale fractures that maintain or enhance permeability and reactive surface area—then the cost of in situ carbon mineralization in peridotite could be relatively low (e.g., Figure 6.17), similar to estimated costs for nth-of-a-kind basalt carbonation processes similar to CarbFix, and approximately the same as for injection of CO_2 into pore space. Where peridotite is abundant, then, this could be the optimal storage method for CO_2. And finally, as for direct air capture via in situ carbon mineralization driven by circulation of surface water through peridotite, in situ CO_2 storage via injection of CO_2-rich fluids into peridotite could be combined with geothermal power generation.

In the lower 48 United States, potential sites for in situ CO_2 storage in peridotite are abundant near both coasts (Krevor et al., 2009). In order to realize enhanced reaction rates at elevated temperature (Figure 6.18), areas of high heat flow are preferred, and these are localized in the western states. One of the largest peridotite massifs in North America, the Trinity peridotite in northern California, dips beneath the Cascade volcanic front (Fuis et al., 1987), an area of high heat flow with elevated temperatures at shallow depth (Bonner et al., 2003; Ingebritsen and Mariner, 2010), ideal for both geothermal power production and carbon mineralization in peridotite. Similarly, smaller bodies of peridotite flank the geothermal area in the Geysers region of northern California (Sadowski et al., 2016), near the Calpine power plant, which is the largest geothermal power plant in the world.

IMPACT POTENTIAL

Geologic storage of CO_2 in ultramafic, mafic, and sedimentary formations has the potential to accommodate 10s of billions of tons of CO_2 per year, and ultimately store 1000s of trillions of tons. This chapter has focused on geologic storage in ultramafic formations, and Chapter 7 discusses storage in sedimentary formations. Together with increasing the carbon content of soils and the oceans, geological storage is one of a

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[4] Preliminary data indicate concentrations of dissolved metals such as Ni and Cr, which are abundant in peridotite, are very low in peridotite-hosted aquifers, well within EPA safe drinking water limits (Amelia Vankeuren, personal communication, 2016).

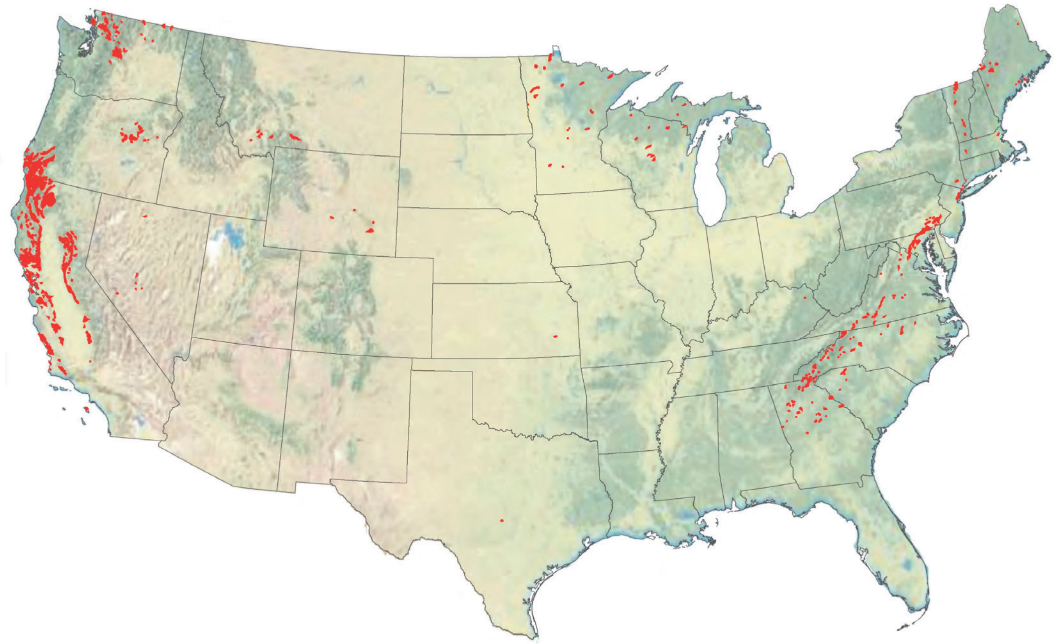

FIGURE 6.18 Ultramafic rock formations at the surface in the United States.
NOTES: In addition to these U.S. resources, peridotite in blocks of oceanic crust and mantle thrust onland (ophiolites) is found on all continents, with a total peridotite mass between 10^{14} and 10^{15} tons within 3 km of the surface. The largest is the "Samail ophiolite," in the Sultanate of Oman and the United Arab Emirates. It contains approximately 5×10^{13} tons of peridotite within 3 km of the surface (Kelemen and Matter, 2008). Other individual ophiolites including peridotite bodies with a similar scale are in New Caledonia, Papua New Guinea, and Albania. The gigantic Bushveld igneous layered intrusion in South Africa contains more than 10^{13} tons of peridotite and is very close to a district of intensive coal mining and coal-fired power generation, supplying electricity to most of the country. The similar Stillwater intrusion in Montana contains almost 10^{12} tons of peridotite. Continental mantle peridotite massifs (exclusive of ophiolites), including the Beni Boussera massif in Morocco and the Ronda massif in southeastern Spain, have a combined mass of about 10^{12} tons.
SOURCE: Krevor et al., 2009.

few options that could accommodate CO_2 removed from air at this (required) scale. Processes that involve billions of tons of fluid and rock inevitably have a substantial impact. It remains to be seen whether society is willing to tolerate these impacts in order to mitigate past and continuing greenhouse gas emissions.

Although greenhouse gas mitigation is the primary target, carbon mineralization has secondary benefits. In particular, the development of engineered methods to control feedbacks between chemical and physical processes could have other important applications, such as extraction of oil and gas from tight reservoirs, in situ solution mining (e.g., for uranium), and production of geothermal power. In addition, in some cases ex situ carbon mineralization acts to mitigate environmental hazards. For example, fibrous asbestos poses a significant health hazard where it is present at the surface, as in mine tailings. In this context, carbonation of chrysotile asbestos reduces the hazard. Similarly, carbonation of some kinds of alkaline industrial wastes can significantly ameliorate the risk of chemical contamination. Moreover, there is a small but robust market for magnesium carbonate, $MgCO_3$, which is sold for $100-1,000/t depending on purity.

All of the potential negative impacts of carbon storage in sedimentary formations—particularly contamination of water resources and induced earthquakes (see Chapter 7)—may also apply to carbon mineralization projects. Preliminary data suggest that the risk of water contamination risk is small. For example, Ni and Cr concentrations in natural carbon mineralization systems are orders of magnitude lower than U.S. Environmental Protection Agency (EPA) limits for safe drinking water (Amelia VanKeuren, personal communication, 2017). Whether this observation holds true for engineered systems will need to be tested. Earthquakes may be triggered because in situ subsurface carbon mineralization increases the solid volume, increasing stresses that could cause fracture. Theoretical considerations and observations of the extent of naturally formed carbonate veins suggest that most reaction-driven fracture events are likely to be small, magnitude 1 or less. As a general rule, the size of fracture events should be limited by the low yield strength of fractured rocks within a few km of Earth's surface, which is the likely target depth for in situ carbon mineralization. However, larger scale deformation associated with Mt/y-scale CO_2 injections could possibly lead to larger-scale failures and will need to be modeled and monitored.

SUMMARY: COST AND CAPACITY OF CARBON MINERALIZATION METHODS

This chapter outlined several proposed methods for engineered acceleration of natural carbon mineralization processes, to achieve either solid storage of CO_2, or combined mineral capture from air and storage. Here we summarize the data in Tables 6.1 and 6.2 to provide a concise evaluation of the cost and capacity for various proposed methods, as compared to direct air capture systems and/or storage of supercritical CO_2 fluid in pore space.

Most ex situ methods for solid storage via carbon mineralization—using fluids enriched in CO_2 compared to air and water in CO_2 exchange equilibrium with air—are significantly more expensive than storage of supercritical CO_2 fluid in subsurface pore space. However, in some cases carbon mineralization acts to mitigate environmental hazards, such as asbestos in ultramafic mine tailings, and toxins in alkaline industrial wastes, which may add value. Research on utilization of reaction products, for example for building materials, or in the supply chain for conversion of CO_2 to CH_4 and more complex hydrocarbons, is ongoing. Carbon capture, utilization, and storage is the subject of a separate National Academies study on "Developing a Research Agenda for Utilization of Gaseous Carbon Waste Streams."[5]

Surficial and in situ methods of solid storage, using fluids enriched in CO_2, may be cost competitive with storage in pore space (Figure 6.19). They may also have some potential advantages because storage is in permanent, inert carbonate minerals with little risk of groundwater contamination, and may be a regionally appropriate technology.

Combined mineral capture from air and solid storage, via surficial processes using existing ultramafic mine tailings, could be a relatively inexpensive and straightforward technology, but has a limited storage capacity. Current, highly approximate cost estimates suggest that mining, crushing, and perhaps additional milling of appropriate lithologies—with a focus on mantle peridotite—for the purpose of mineral capture from air and storage via enhanced weathering may be cost-competitive with direct air capture systems, within the uncertainties for cost estimates for each type of process (Figure 6.20).

In situ mineral capture and storage is potentially cost-competitive with direct air capture systems, and offers a gigantic storage potential, if negative feedbacks such as clogging can be avoided, and positive feedbacks such as reaction-driven cracking can be harnessed.

All of these avenues for mitigating CO_2 emissions via carbon mineralization warrant continued, accelerated research programs, including laboratory experiments, numerical modeling, investigation of social and regulatory factors, and pilot projects in the United States.

RECOMMENDED RESEARCH AGENDA

Carbon Mineralization Kinetics

Comparison of rates for different mineral, rock, and synthetic solid reactants is hampered by a lack of consistency in experimental methods. Comparative studies of carbonation rates for different materials, at the same temperature, pressure, $P(CO_2)$, grain size, surface area, and fluid composition, remain a high priority that is achievable

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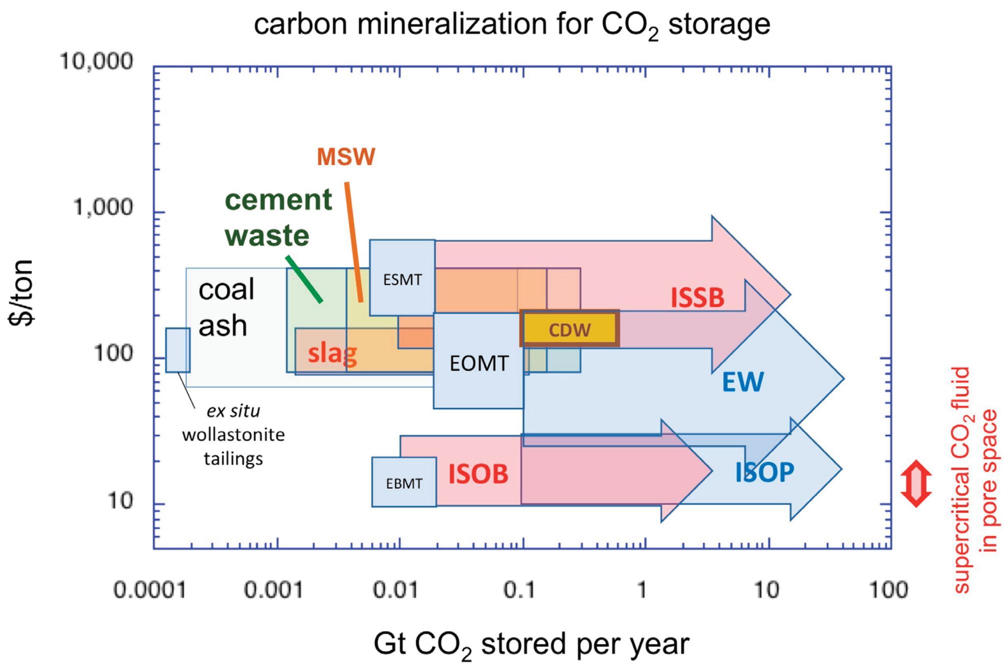
[5] See http://nas-sites.org/dels/studies/gcwu (accessed January 28, 2019).



ESMT: *ex situ* serpentine-rich mine tailings; EOMT: *ex situ* olivine-rich mine tailings; EBMT: *ex situ* brucite-rich mine tailings; ISSB: *in situ* seafloor basalt; ISOB: *in situ* onland basalt; ISOP: *in situ* onland peridotite; EW: enhanced weathering peridotite quarried & ground for mineralization; MSW: municipal solid waste; CDW: construction & demolition waste

FIGURE 6.19 Summary of annual storage potential vs cost in US\$/tCO_2 for proposed solid storage using fluids enriched in CO_2, based on values in Table 6.1 and references therein.
NOTE: Costs should be compared to the cost of storage of supercritical CO_2 in subsurface pore space, ~\$10-20/tCO_2 (Chapter 7).

at low cost. Our compilation is missing key data for carbon mineralization rates in alkaline industrial wastes. A compilation of experimental data for these materials, allowing comparison using units such as mol/(m^2 s), or mass fraction per second at a common grain size, is a worthy research goal in itself, and would likely reveal a need for additional, comparative experimental studies.

Ex Situ Carbon Mineralization

Laboratory studies of ex situ carbon mineralization processes for CO_2 storage have been extensive and are ongoing. Due to the relatively high cost of *ex situ* mineralization compared to storage of supercritical CO_2 in pore space (Table 6.1), the focus on *ex situ* methods in the past decade has been on producing economically valuable commodities as well as storing captured CO_2. Carbon capture, utilization and storage

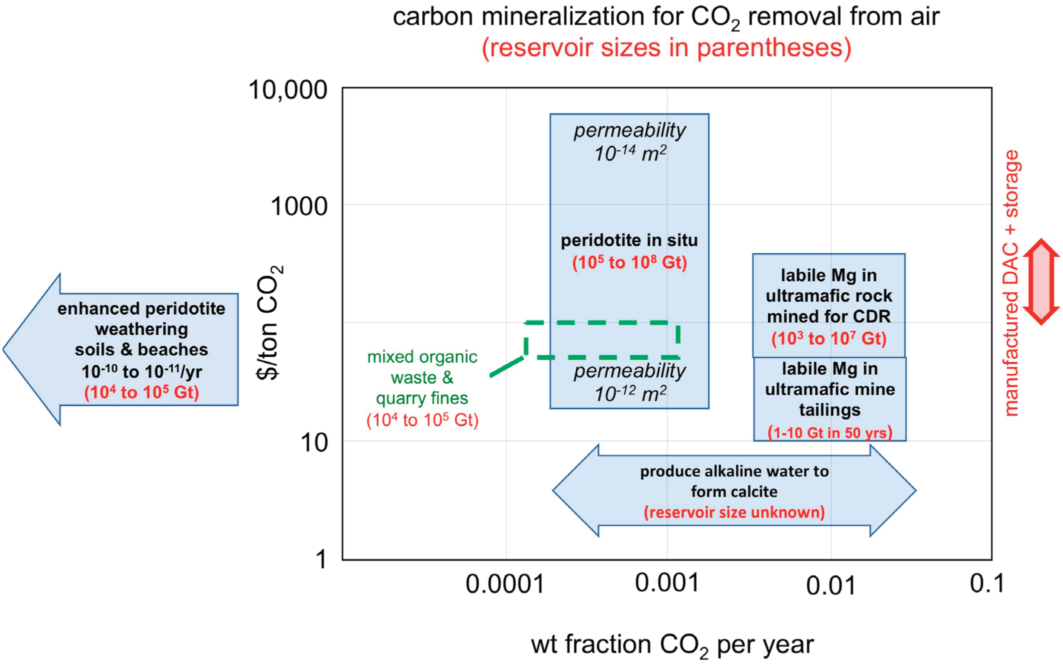


FIGURE 6.20 Summary of weight fraction of CO_2 added to reservoirs per year vs cost of storage in US$/t for proposed methods of CO_2 capture from air and storage via carbon mineralization, based on values in Table 6.2, and references therein.
NOTE: The size of potential storage reservoirs is indicated in parentheses for each proposed method. Costs are compared to the cost of direct air capture systems, ~$100-600/t CO_2 (Chapter 5).

is the subject of a separate National Academies study on “Developing a Research Agenda for Utilization of Gaseous Carbon Waste Streams.”[6] Creation of carbon-added, value-added aggregate for concrete is one area of active work, as is air-to-fuels via conversion of captured CO_2 to hydrocarbons. Rock reactants, particularly mantle peridotite, could potentially be used to achieve this conversion (e.g., McCollom et al., 2010), although direct air capture technologies may be a less expensive source of CO_2. Research in these directions is partly supported by the Department of Energy (DOE), and there seems to be substantial grant and venture-capital support.

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[6] See http://nassites.org/dels/studies/gcwu (accessed January 28, 2019).

Surficial Carbon Mineralization in Mine Tailings, Industrial Wastes, and Sediments

Based on extensive research by a few groups focused on this topic, surficial carbon mineralization for solid storage or for mineral capture and storage is ready for kiloton to megaton per year field experiments, together with extensive field inventories and laboratory characterization of the reactivity of various potential solid reactants. Field experiments on mine tailings and industrial wastes may be particularly good opportunities for university-industry and/or government-industry partnerships, as illustrated by a recently initiated collaboration involving the diamond-producer DeBeers and several academic research groups (Mervine et al., 2017). Significant limitations are the relatively small mass of accumulated and annually produced of mine-tailings, and the relatively limited CO_2 storage capacity of industrial wastes with low concentrations of Mg and Ca. More effort needs to be focused on potential effects of geochemical contamination, because in many cases implementation is likely to be close to surface water and groundwater resources. In the United States, carbonation of ultramafic mine tailings could be combined with efforts to reduce asbestos hazard at these same sites. Carbonation of industrial wastes to mitigate hazards is of potential interest to EPA and DOE.

A basic research area with high potential, but whose effectiveness and cost are currently impossible to assess, is microbial acceleration of carbon mineralization in mine tailings (e.g., Power et al., 2013a). This should be funded as laboratory-based investigation by several research groups.

Another research priority concerns optimization of various pretreatment strategies, including heat pretreatment, grinding/comminution processes, and new technological approaches such as microwave treatment, to increase the rapidly reacting labile Mg content of tailings and/or to reduce process costs per ton of CO_2. Such approaches are currently used to enhance metal extraction but could also be followed to enhance carbon mineralization. For example, grinding to separate small sulfide or metal oxide minerals for liberation and flotation may exceed the amount of grinding needed to access labile Mg. Thus, it may be possible to reduce the cost and energy intensity of quarrying and grinding rock for carbon mineralization alone. Moreover, where the goals are both metal extraction and carbon mineralization, parts of ore deposits with high labile Mg concentrations could be mined, even if these include rock volumes with a relatively low ore grade. Industry-academic partnerships, with research funding from the National Science Foundation (NSF), seem best suited to address such optimization issues.

Progress on verification protocols and regulatory and pricing frameworks is another priority. Because of recent, damaging failures of tailings dams in the United States and Canada, the current regulatory and social environment discourages innovation in the design of tailings storage facilities. Creating a safe research space to explore innovation could ultimately lead to safer and more efficient operations. Funding could come from current and prospective industry partners.

Some research groups have begun investigating hybrids of *ex situ* methods (bringing solid reactants to the site of CO_2 capture) and *in situ* methods (transporting captured CO_2 to large rock reservoirs). Work has focused on local modifications to ultramafic mine tailings, particularly mine tailings from highly altered serpentinites that include abundant brucite (and asbestiform chrysotile) (Alt et al., 2007; Assima et al., 2012, 2013a, b, 2014a, b, c, d; Bea et al., 2012; Gadikota et al., 2014; Hansen et al., 2005; Harrison et al., 2013, 2015, 2016; Larachi et al., 2010, 2012; McCutcheon et al., 2014, 2015; Mervine et al., 2017; Power et al., 2007, 2009, 2010, 2011, 2013a, b, c, 2016; Pronost et al., 2011, 2012; Sarvaramini et al., 2014; Thom et al., 2013; Wilson et al., 2006, 2009a, b, 2010, 2011, 2014). Suggested modifications are as simple as stirring tailings, depositing them in thinner layers, and sprinkling water on them to transport atmospheric CO_2 deeper into the pile for direct air capture. Other modifications have been more innovative, such as introducing CO_2-rich gas or fluid into slurry pipes that transport tailings. Two recent studies demonstrate the potential for up to a million-fold acceleration of carbon mineralization rates by sparging CO_2-rich gas through mine tailings (Assima et al., 2013a; Harrison et al., 2013). Their experiments achieved rates at ambient surface temperatures that approach or exceed the highest laboratory rates for carbon mineralization at elevated temperature and pressure, at least for CO_2 uptake of 3 to 10 wt%. This is a promising avenue of research, which should be pursued in both laboratory experiments and field-scale pilot studies at several mine sites. Similar techniques might also be applied to alkaline industrial waste heaps.

Carbon mineralization in crushed ultramafic materials may be viable in peridotite-rich alluvial gravels, which have high surface area to volume ratios and are present along some tectonic plate boundaries. A study of one ancient deposit found that it was already extensively carbonated (Beinlich et al., 2010). However, other basins with large volumes of peridotite gravel should be investigated to determine the extent to which they offer potential reactants for engineered carbon mineralization. For example, peridotite-rich sediments derived from mechanical weathering of the Samail ophiolite in Oman and the United Arab Emirates are present in km-thick formations beneath the Batinah coastal plain (e.g., Al Lazki et al., 2002) and in the extensive Barzaman Formation south and west of the ophiolite (Lacinska et al., 2014; Radies et al., 2004; Styles et al., 2006). While some of the ultramafic clasts in these rocks are extensively altered, subsurface exploration for less altered, more reactive potential CO_2 reservoirs in these settings is warranted. In the United States, this exploration might be best undertaken by the USGS.

In Situ Carbon Mineralization in Basaltic Lavas

The Wallula and CarbFix projects have established the viability of combined CO_2 storage in pore space and carbon mineralization in basaltic lavas. In particular, the strategy used at CarbFix, combining solution trapping of CO_2 dissolved in water with rapid carbon mineralization, demonstrates that this combination need not consume huge volumes of water, as many feared, and opens the opportunity for extensive CO_2 storage in relatively accessible, easily characterized, near-surface basalt formations.

The logical next step is megaton per year experiments in the United States. To date, the emphasis has been on the large volume Columbia River and East Coast Triassic Flood Basalt Provinces (Figure 6.10). In addition, the volcanic Cascade volcanic arc, especially in Oregon and northernmost California, may offer reservoirs with high storage potential. Potential basalt reservoirs will have layers that are rich in highly reactive, amorphous volcanic glass, have high permeability, and have relatively high temperatures at shallow depth. Ideally, these layers will be bounded by low permeability barriers, with little faulting or deformation. However, an impermeable caprock to prevent leakage is not required for the solution trapping strategy used at CarbFix. This strategy might be appropriate for shallow, glassy lava flows that are more reactive than most flood basalt formations. In moving from small- to medium-scale pilot experiments, research groups will have to focus on potential chemical contamination of nearby aquifers and surface waters, and on the risk of induced earthquakes.

This extensive scoping—focused on the reactivity and capacity of reservoir rocks and the availability of impermeable cap rocks—should be funded by DOE and USGS, potentially in collaboration with state governments and/or industry. Medium-scale pilot projects are likely to cost 10s of millions of dollars per year, with substantial funding coming from DOE (Appendix F provides a schematic budget for such a project). States that have implemented carbon taxes or offer other incentives for carbon management may be willing partners, together with industries seeking offsets in these states. Once sites for pilot experiments are chosen, it will be important to implement the lessons of CarbFix in designing tracer studies. Experiments should focus on optimization of one- and two-phase injection strategies, particularly for shallow reservoirs where solution trapping is necessary. Longer duration, higher flux experiments should examine evolution of subsurface reaction fronts, determine the nature of local carbon mineralization reactions (i.e., what minerals are reacting, at what grain sizes, and at what rates?), and especially feedbacks affecting permeability and reactive surface area. Recommended laboratory experiments and numerical modeling studies to address these feedbacks for in situ carbon mineralization in basaltic lavas are essentially identical to those for in situ mineralization in ultramafic rocks (see the next section, "In situ Carbon Mineralization in Ultramafic Rocks").

To date, there has been little interest in combined mineral capture and storage in basalt reservoirs, probably, because there are few examples of extensive, natural carbon mineralization in basalt at low- temperature, near-surface conditions, and because laboratory studies have found slower carbon mineralization rates in basalts compared to ultramafic rocks such as mantle peridotites. (An exception is glassy basaltic lavas.) As a result, pilot studies in most basalt formations will be focused on injection of CO_2-rich fluids to achieve a combination of storage in pore space and solid storage. Because injection of CO_2 is subject to federal regulations governing Class VI wells, extensive site characterization, monitoring, and post-injection site closure operations will be required.[7]

Experimental carbon mineralization rates and capacities for different combinations of basalt types and fluid compositions vary widely. Quantifying the controls on basalt carbonation rates is another high priority, comparatively low-cost opportunity for laboratory research, which should be largely supported by DOE.

In Situ Carbon Mineralization in Ultramafic Rocks

In situ carbon mineralization in ultramafic rocks, mainly in large massifs of tectonically exposed mantle peridotite, represents a high-risk, high-reward opportunity, requiring extensive basic research to evaluate its practicality, combined with one or more small-scale field experiments over the next decade.

Ultramafic rock tends to have low porosity and extensive fracturing. These characteristics create the potential for important feedbacks between carbon mineralization and permeability. Consequently, extensive studies of chemo-mechanical processes are required to determine the conditions favoring reaction-driven cracking and other positive feedbacks, as well as the conditions leading to clogging of pore space and passivation via armoring of reactive surfaces. A crucial research goal is to create a

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[7] See https://www.epa.gov/uic/class-vi-guidance-documents (accessed January 28, 2019).

"phase diagram" delineating the conditions favoring positive and negative feedbacks for carbon mineralization in ultramafic rocks.

If reaction-driven cracking were well understood, it would be possible to engineer conditions that generate ramified fracture networks at the grain scale. Such approaches could be valuable for a variety of technologies, including CO_2 capture and storage, geothermal power generation, in situ mining, and extraction of oil and gas from low permeability reservoirs. Similarly, avoiding reaction-driven cracking is important for ensuring the long-term integrity of impermeable cap rocks and well cement in boreholes for subsurface CO_2 and hydrocarbon reservoirs.

Increasingly, researchers are realizing that nano-scale material characteristics (mineral fluid surface energy, sorptivity, disjoining pressure) may play a key role in controlling the bifurcation between clogging and cracking. Because these characteristics vary in unpredictable ways from one material to another, research is moving away from simple analog systems (hydration or carbonation of CaO, MgO, and $CaSO_4$) toward experiments involving the most geologically relevant rock formations (e.g., peridotite and basalt for CO_2 capture and storage, shale for oil and gas, and sandstone for uranium). A growing community is working on these topics, inspired in part by the problems and promise of in situ mineral carbonation, and the dialog among different research groups around the world promises to be productive. U.S. participation and leadership in this emerging basic science field deserves continued, focused support from NSF and DOE.

The above topics are ideal for laboratory and numerical modeling approaches and will be particularly fruitful where the two are combined and constrained using field observations of natural systems. Both NSF and DOE fund basic research on feedbacks during reactive fluid transport. Expanded support from NSF and DOE would enable the integration of laboratory, modeling, and field approaches.

In parallel with laboratory research and numerical modeling, we recommend funding for two or three small- to medium-scale (~1 to 100 kt/y) field experiments. Such experiments would investigate the viability of in situ carbon mineralization during (a) mineral capture and storage of CO_2 via circulation of surface water through peridotite and (b) solid storage of CO_2 via circulation of CO_2-rich fluids through peridotite. They could also be used to optimize engineered methods to achieve rapid carbon mineralization and minimize negative feedbacks.

We envision multistep pilot projects on in situ carbon mineralization in ultramafic rocks, with gradually increasing cost, ambition, and risk and funded by DOE, USGS, and/or state sources, ideally in combination with industry partners. Such projects will first require scoping efforts—characterizing physical properties and the suitability of rock formations for possible pilot projects and assessing the long-term potential for significant CO_2 storage reservoirs. Scoping will also include a significant component of policy research, public outreach, and investigation of political and social factors in nearby communities and regions.

Assuming that geologically and socially appropriate sites can be identified, a next step would be to produce water from existing, alkaline, carbon-depleted aquifers for direct uptake of CO_2 from air to form carbonate minerals in travertine deposits on the surface, and dissolved bicarbonate in surface water. The size, permeability, productivity, and physical and chemical recharge rates of such aquifers are unknown and could readily be evaluated for several sites at a relatively low cost. Experiments could then progress to injecting recycled water into peridotite aquifers, with continued characterization of injectivity, permeability, volume, and subsurface rates of subsurface CO_2 mineralization. Pending a successful outcome of this step (CO_2 removal from circulating fluids, no sustained decrease in permeability), experiments could progress to investigating deeper circulation into hotter rock formations, with faster carbon mineralization rates. A final set of experiments could include injecting fluids with high CO_2 concentration to evaluate proposed storage of CO_2 captured elsewhere. The steps involving production and re-injection of groundwater depend on state and local regulations but might be relatively straightforward to implement. Because injection of fluids enriched in CO_2 is subject to federal regulations governing Class VI wells, the final set of experiments would require significantly more site characterization, monitoring, and post-injection site closure operations.

The likely cost of such a phased experiment, carried to completion, is estimated as \$10-20M/y, based on the costs of CarbFix Phase I (Aradóttir, personal communication, 2017) and a notional budget for a large-scale experiment on CO_2 storage in basalt (Appendix F, Table F.3). Because carbon mineralization rates in peridotite are optimal at ~185°C, there is potential synergy between carbon mineralization and geothermal power generation. The best region to explore this synergy in the United States is northern California, where carbon management incentives and an active geothermal industry might facilitate combined DOE, state, and industry participation.

Improved Public Dissemination and Impact Assessment

Beyond the research to advance understanding of basic scientific processes and develop pilot-scale tests of carbon mineralization technologies for CO_2 removal and storage, the committee identified three other areas in need of additional research. Included in the research agenda is the call for the development of a database for carbon mineralization to ensure that the results of the research activities are disseminated broadly to the research community. Further, research is also needed to examine the social and environmental impacts of an expanded extraction industry to meet the needs of scaling up these NETs. Finally, the committee believes research is needed to assess the environmental impacts of minerals additions to terrestrial, coastal, and marine environments. This research would be shared with the research agenda for terrestrial carbon removal and sequestration (Chapter 3).

Cost of the Research Agenda

There is far less experience and data on even kiloton-per-year storage of CO_2 via carbon mineralization, let alone megaton- and gigaton-per-year processes, compared to experience and data on storage of supercritical CO_2 in deep sedimentary formations. This is true largely because the economic incentives and technical expertise for injecting supercritical CO_2 for enhanced oil recovery are not matched by opportunities associated with carbon mineralization. Significant decadal progress on this research agenda requires a mix of basic and applied research aimed toward the same overall outcome (Table 6.3).

Implementation of the Research Agenda

While the research topics enumerated above appeal to research scientists, it can be difficult to obtain federal grant support for such studies, in part because the research falls between the perceived domains of the NSF Directorate for Geosciences, where many of the research topics may be viewed as "too applied," and DOE, where the same topics may be viewed as "too theoretical." Some DOE programs bridge the gap between basic and applied science, but funding flows primarily to the National Laboratories. An example is DOE's Crosscutting Subsurface Technology and Engineering Research, Development, & Demonstration (SubTER) initiative,[8] which covers National Laboratory investigations on hydraulic fracture and induced earthquakes related to oil and gas extraction. Developing a similar grants program at DOE would enable university research on cracking versus clogging during reactive transport of fluids in fractured porous media, chemo-mechanical feedback during carbon mineralization, geothermal energy production, and in situ solution mining.

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[8] See https://www.energy.gov/subsurface-science-technology-engineering-and-rd-crosscut-subter (accessed January 28, 2019).

TABLE 6.3 Carbon Mineralization Research Agenda Budget

	Typical Academic Grants (Approximate annual amount $500K)	National Lab and USGS Projects (Approximate annual amount $1.5M)	Cost/y	Years	Total	Barriers the research will address, or new frontier[a]
Basic Research						
Kinetics	5	2	$5.5M	10	$55M	STU: experiments at common T, P(CO_2), fluid composition to establish quantitative framework and enable comparisons and optimization.
Rock mechanics	6	2	$6M	10	$60M	Frontier: exploration of positive and negative feedbacks between reaction and fluid flow, for in situ carbon mineralization, in situ mining, geothermal power generation, extraction of oil and gas from tight reservoirs, ensuring integrity of reservoir caprock and wellbore cement.
Numerical modeling	6	2	$6M	10	$60M	As above
Field studies	4	2	$5M	10	$50M	As above

Scoping for pilot sites	0	5	$7.5M	5	$37.5M	STU, OENV, G
Development of a resource database for carbon mineralization	4	0	$2M	5	$10M	STU, PBSU
Examining the social and environmental impact of an expanded extraction industry for the purpose of carbon removal	10	0	$5M	10	$50M	C, OENV, PBSU
Reactive mineral additions to soils	3	0	$3M	10	$30M	Frontier: Assess weathering rates of reactive minerals (i.e., olivine) added to agricultural soils and effects on agricultural productivity, soil carbon, nutrient use, water use, and albedo. Determine the carbon storage limits that can be achieved with mineral addition.
Studying the environmental impact of mineral addition to terrestrial, coastal and marine environments	8	4	$10M	10	$100M	STU, C, OENV, G, PBSU

continued

TABLE 6.3 Continued

	Number of academic/national lab/ industrial partnerships	**Total cost/project/ year**				
Pilot Studies						
Ex situ[b]	2	$250K	$500K	10	$5M	C, EN, OENV, G, M&V, PBSU
Mine tailings, alkaline wastes	4	$250K	$1M	10	$10M	STU, C, EN, OENV, G, M&V, PBSU
Soils, beaches	3	$1M	$3M	10	$30M	Frontier: Challenging field-scale characterization of slow rates over large areas with poor controls on natural inputs and outputs
In situ basalt[c]	1	$10M	$10M	10	$100M	STU,C, EN, OENV, G, M&V, PBSU

in situ peridotite[c]	1	\$10M	\$10M	10	\$100M	Frontier: No prior experiments on field scale, initial low porosity requires stimulation and/or practical knowledge of positive feedbacks such as reaction-driven cracking.

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[a] STU = scientific and technical understanding, C = cost, EN = energy use, OENV = other environmental concerns, G = governance, M&V = monitoring and verification, PBSU = practical barriers to scale-up, Frontier = long term research.

[b] Lab kinetics above, relevant to all categories, but leave larger-scale ex situ studies to the carbon capture, utilization, and storage community.

[c] Constant annual cost listed here, phased project with increasing annual expenses for successive phases described in text and Appendix F, Table F.3.

Research topics spanning NSF and DOE domains could be facilitated by establishing a formal NSF-DOE partnership, focused on funding research on greenhouse gas mitigation (not restricted to CO_2 removal from air). Such a partnership could resemble several successful initiatives within NSF's Directorate for Geosciences, such as the RIDGE, MARGINS, and GeoPRISMS Programs, in which the Earth Sciences and Marine Sciences Divisions cooperated to fund multidisciplinary research "across the shoreline." Examples of interagency cooperation of this kind include volcano monitoring and investigations of dark matter.

CHAPTER SEVEN

Sequestration of Supercritical CO_2 in Deep Sedimentary Geological Formations

INTRODUCTION

Geological sequestration is a necessary complement to direct air capture of carbon dioxide (CO_2) (see Chapter 5) and bioenergy with carbon capture and sequestration (Chapter 4). After CO_2 is captured, it is compressed into a supercritical fluid, then injected down a well into a geologic formation that is deep enough for the CO_2 to remain as a supercritical fluid, typically 1 km or more. Compression of the gas to a supercritical fluid allows more CO_2 to be sequestered. This is due to the high-density of the fluid (~600 kg/m^3) relative to gaseous CO_2 and the reduced buoyancy forces in water-filled geological formations, although the system maintains a strong buoyant drive between CO_2 and brine (Benson et al., 2005).

Suitable geological formations for storing CO_2 comprise a porous and permeable reservoir rock, overlain by an impermeable rock (Figure 7.1). Prospective reservoir rocks include sandstone, limestone, dolomite, or mixtures of these rock types. Because the supercritical CO_2 is less dense than the fluids that initially fill the pore spaces in the rocks, it will rise by buoyancy forces through the reservoir rocks until it encounters a low permeability rock, typically called a reservoir seal. Seals are composed of shale, anhydrite, or low permeability carbonate rocks. Once trapped below the seal the CO_2 is expected to remain sequestered permanently unless the CO_2 encounters a permeable fault or fracture in the seal or a leaky wellbore.

Reservoir rocks are characterized by rock type and by whether the pore spaces in the rocks contain salty water or are filled with oil or gas. Oil and gas reservoirs are further characterized by whether the injected CO_2 is also used for increasing oil or gas recovery, a process referred to as CO_2 enhanced oil or gas recovery. Coalbeds have also been investigated for CO_2 sequestration, but technical challenges have precluded large-scale testing or application (Gale and Freund, 2001; Shi and Durucan, 2005). More recently, hydraulically fractured shale formations have also been suggested as an option for sequestration, with or without enhanced hydrocarbon recovery (Tao and

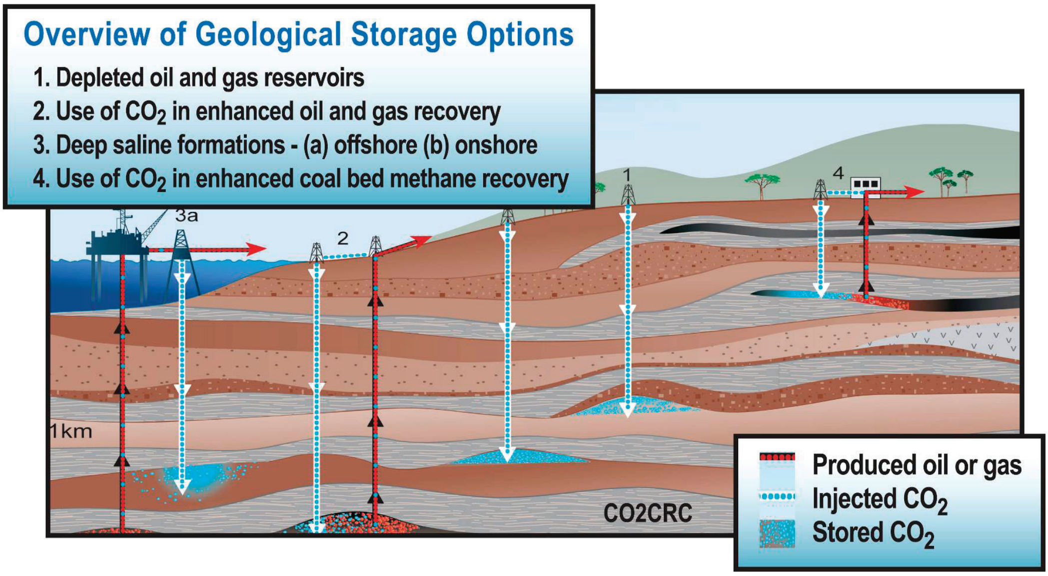

FIGURE 7.1 Options for geological storage in sedimentary rocks. SOURCE: Benson et al. (2005).

Clarens, 2013). However, there are many practical challenges to accessing the storage volume at the needed rates (Edwards et al., 2015).

Sequestration of supercritical CO_2 in the pore spaces of sedimentary rocks is the most mature of the options available today for reliable storage. Several comprehensive reviews and research roadmaps lay out the scientific and engineering basis for secure sequestration; discuss site characterization and selection; describe effective monitoring and risk assessment and management approaches; and estimate global sequestration capacity and costs (Bachu, 2015; de Coninck and Benson, 2014; DOE, 2017d, g; Rubin et al., 2015; U.S. Geological Survey, 2013). More importantly, nearly a half-century of experience with CO_2 injection for enhanced oil recovery (EOR), and nearly two decades of commercial experience with saline aquifer sequestration are available today (Furre et al., 2017; Hansen et al., 2013; IEA, 2016; Koottungal, 2014; Wilson and Monea, 2004). Finally, a large number of pilot-scale experiments have been carried out to test various aspects of sequestration, including methods for monitoring the fate and transport of CO_2 in the surface and leakage (Ajo-Franklin et al., 2013; Greenberg et al., 2017; Hovorka et al., 2006; Ivandic et al., 2015; Jenkins et al., 2012; Mito et al., 2008; Rodosta et al., 2017; Spangler et al., 2010).

As a result of extensive research and experience, scientists now have a good idea of the global and regional distribution of capacity to sequester CO_2, integrity, risks, and costs of geologic sequestration. Saline aquifer and CO_2-EOR projects are currently sequestering about 31.5 Mt/y of anthropogenic CO_2 (GCCSI, 2017). A technical potential of 2,000 Gt CO_2 is likely for the coming century, enough to make a substantive contribution to greenhouse gas mitigation strategies (IPCC, 2005). The 2,000 Gt technical potential is large compared to 125 Gt captured and sequestered from fossil fuels and industrial emissions required by 2100 to meet the 2°C target of sequestration (IEA, 2014). This sequestration capacity may not be co-located with all large sources of CO_2 emissions, thus requiring either large scale and long-distance CO_2 transport by pipelines or ships for some of the emission sources. Carbon capture and sequestration is expected to contribute about 14 percent of the emissions reductions needed to stabilize the climate at 2°C warming (IPCC, 2005). The primary impediments to scaling up to that level concern geology (e.g., site characterization), regulations (e.g., difficult permitting), as well as real and perceived risks (e.g., induced seismicity, leaks). This chapter summarizes what has been learned about geologic sequestration and discusses research needed to ensure secure and reliable sequestration of gigatons of anthropogenic CO_2 per year.

BACKGROUND: REQUIREMENTS FOR SECURE AND RELIABLE SEQUESTRATION

Geological Formations Suitable for Sequestration

There are two basic requirements for secure sequestration in sedimentary formations. The first is a thick reservoir, typically a sandstone or carbonate, with sufficient porosity to sequester large volumes of CO_2 (~50-100 Mt/project) and sufficient permeability to accommodate injection at commercially meaningful rates (~Mt/year). The second is a seal, typically composed of shale, with high enough capillary entry pressure and low enough permeability to retain the CO_2 over geological time periods. Beyond this are site-specific requirements regarding the absence of permeable faults and fractures penetrating the seal, a known and ideally low number of existing wells that could provide leakage pathways, favorable geomechanical conditions to avoid fracturing the reservoir or seal during injection, suitable conditions for monitoring, low likelihood of affecting groundwater, and compatibility with existing land and resource use.

Sequestration security may also be enhanced by secondary trapping mechanisms that act over time to reduce the risk of leakage of CO_2 out of the storage reservoir. These mechanisms include solubility trapping (dissolution of CO_2 into the brine), residual gas trapping (immobilization by capillary forces in the post-injection period), and mineralization through geochemical interactions between the CO_2, brine, and rock (Emami-Meybodi et al., 2015; Krevor et al., 2015; Talman, 2015; Zhang and DePaolo, 2017). The relative importance of these secondary trapping mechanisms is highly site specific (Figure 7.2) and should be assessed using advanced multiphysics, multiscale numerical simulation models. For example, in a closed structural trap (left panel), solubility trapping is slow and capillary trapping is minimal because the CO_2 does not move far. In a hydrodynamic trap, such as a large saline aquifer (middle panel), the CO_2 may migrate a substantial distance horizontally. In this situation, solubility trapping is more rapid, capillary trapping can be extensive, and mineralization can be enhanced because the CO_2 is exposed to a large volume of water-filled rock.

In some cases, the combination of the secondary processes may be sufficient to entirely mitigate any future risks within decades to centuries after the injection is stopped, whereas in other cases, CO_2 will still remain potentially mobile for thousands of years. Engineering design of a sequestration project can accelerate trapping through optimal placement of injection wells, co-injection or sequential injection of water, time-varying injection rates, and potentially other approaches yet to be developed (Cameron and Durlofsky, 2012; Ide et al., 2007; Pawar et al., 2015).

Modeling and Simulation

Robust numerical modeling of CO_2 plume migration, pressure buildup, geomechanical effects, and geochemical reactions are required for the design, optimization, and performance confirmation of sequestration projects. Finite difference, finite volume,

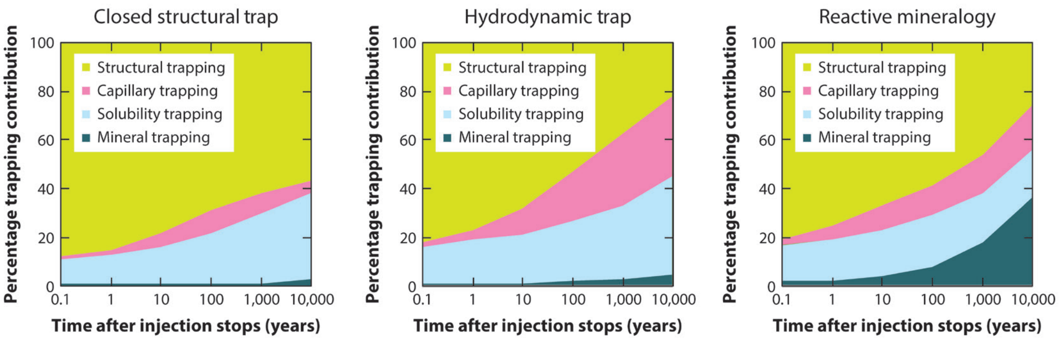

FIGURE 7.2 Secondary trapping mechanisms vary widely depending on the geology, architecture, and hydrogeology of the site.
NOTE: This is for quartz-dominated silicicastic rocks in contrast to the results for peridotite reservoirs, shown in Figure 6.7. SOURCE: de Coninck and Benson (2014).

or finite element approaches for discretizing the subsurface are used to solve a set of coupled nonlinear partial differential equations that describe the processes occurring in the subsurface (DOE, 2017b). Both proprietary and publicly available codes are available for simulating subsurface processes. Intercomparison studies show that calculations from mature codes using similar spatial and temporal discretization, thermodynamic models for fluid properties, and physical processes agree quite well with each other (Class et al., 2009; Pruess et al., 2004). In practice, however, due to the large spatial domains, long time frames, multiphysics nature of these problems, modelers use a variety of approaches for making these simulations more tractable, including using reduced physics models, upscaling, and nonconverged discretizations (Nordbotten et al., 2013). Intercomparisons that provide the flexiblity to use different approaches for solving even simple problems are found to provide large differences in important model outputs such as plume extent, plume center, plume spread, and CO_2 phase distribution, leading to the conclusion that better modeling tools are needed (Nordbotten et al., 2012). Rapid growth in computational power combined with advanced algorithms for solving large sets of coupled nonlinear equations provide the opportunity to make rapid advances in several areas that will support the scale-up to Gt/y sequestration.

In particular, important physical and chemical processes span spatial scales from nanometers to kilometers, and temporal scales from milliseconds to millennia (Figure 7.3). Consequently, spatial and temporal averaging is required to make the simulations tractable. Volume-averaged properties typically rely on empirical parameterizations that are obtained from laboratory experiments conducted on small samples over short periods of time under conditions which may or may not be representative of actual conditions during the sequestration project. For example, relative permeability is used to parameterize how multiple fluids phases (e.g., CO_2 and water) occupy and flow through the rocks. For practical reasons, the flow rate at which these measurements are made is often much higher than the slow flow rates actually experienced during a sequestration project. Computationally intensive and advanced pore-network models and direct solution of the Navier Stokes equations in realistic pore geometries are now being used to bridge these scales, but much remains to be done (Abu-Al-Saud et al., 2017; Raeini et al., 2018). Similar considerations apply to reaction constants for geochemical processes that occur in the reservoir (Zhang and DePaolo, 2017) or parameterization of the onset of convective dissolution in saline formations (Riaz et al., 2006). To reconcile the challenges, multiscale, multiphysics modeling is needed to bridge the gap between scales to accurately parameterize these models. The supercomputers and experimental tools (e.g., U.S. Department of Energy [DOE] light sources) needed to accomplish this are improving quickly, and rapid progress can be expected with sufficient support.

The lack of a sufficient description of the subsurface geology is also a major challenge for modeling subsurface processes. Information about the subsurface is available from drill cuttings, geophysical well logs, seismic surveys, and a variety of additional techniques. However, a complete high-resolution model of the subsurface is available only at the wellbores themselves. Everything between the wellbores should be inferred indirectly through seismic or other types of geophysical imaging. To deal with the uncertainty associated with the lack of complete information, probabilistic geostatistical methods are used to characterize the subsurface (e.g., Caers and Zhang, 2004; Kitanidis, 1997). Stochastic simulations are used to obtain probabilistic estimates of plume migration, trapping fractions, and sequestration capacity.

It is important to point out that alternative approaches for predicting plume migration have been developed, so-called reduced physics models, that retain many of the critical processes but require less data and are much less computationally intensive (MacMinn et al., 2012; Nordbotten et al., 2005; Szulczewski et al., 2012). While not a substitute for complex models that include a realistic representation of the geological

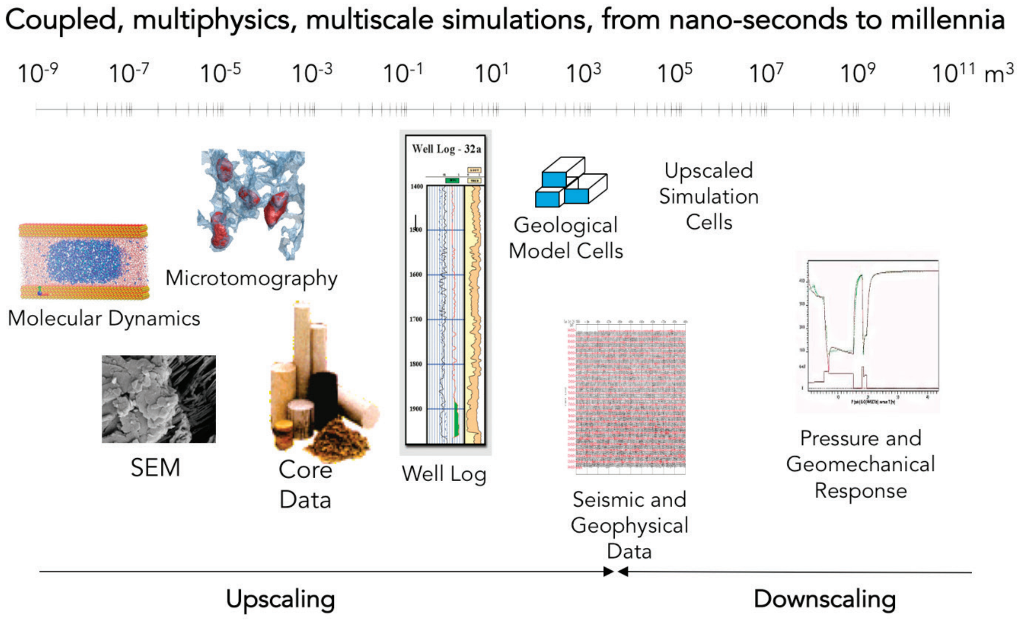

FIGURE 7.3 Illustration of the vast range of relevant spatial scales and relevant processes for geological sequestration of CO_2. SOURCE: Modified from Hamdi Tchelepi, personal communication, May 2018.

setting, they provide useful insights and preliminary estimates of how far the CO_2 will migrate from the injection well, residual trapping, and solubility trapping. The models have also been used to develop dynamic capacity estimates for several basins in the United States (Szulczewski et al., 2012).

Finally, in practice today, simulation models are used in concert with monitoring data in an iterative fashion, which through the process of history-matching allows calibration of the model. Calibrated models are shown to perform well for geological sequestration projects, at least over decades during the injection period as has been shown from the existing large projects and dozens of pilot projects.

Monitoring

To ensure that sequestration projects are safe and effective, it is necessary to track the location of the plume of sequestered CO_2, measure the pressure buildup in and above the storage reservoir, confirm that the injection wells or other wells penetrating the storage formation are not leaking, and look for leakage into groundwater. Requirements or guidelines for monitoring are a key part of government regulations for CO_2 sequestration projects (e.g., EPA, 2010). Numerous pilot tests and commercial operations have demonstrated a wide range of monitoring techniques. Seismic imaging is the most commonly used monitoring method for tracking the location of the CO_2 plume (Ajo-Franklin et al., 2013; Hovorka et al., 2006; Ivanova et al., 2012; Jenkins et al., 2015; Pevzner et al., 2011; White, 2013). An example of the application of seismic imaging for tracking the location of the CO_2 plume is shown in Figure 7.4. The data demonstrate that CO_2 is trapped beneath the seal and that several intra-reservoir shale layers act as baffles to trap CO_2 deep in the reservoir. The map-view image shows that CO_2 is traveling underneath the seal along a north-south axis that coincides with the topography of the seal.

Pressure buildup can be measured in the sequestration reservoir at the injection wells and the monitoring wells, and in aquifers above the storage reservoir. Pressure data from the injection wells is used to ensure that the pressure does not increase to levels that would hydraulically fracture the seal (EPA, 2010). Pressure data from the monitoring wells can be used to assess the extent to which the pressure buildup extends throughout the storage reservoir, which is important for understanding the "area of review"[1] and for predicting how multiple sequestration projects in the same reservoir might interact. Vertically distributed pressure sensors can also be used to

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[1] The region surrounding the geologic sequestration project where underground sources of drinking water may be endangered by the injection activity. The area of review is delineated using computational

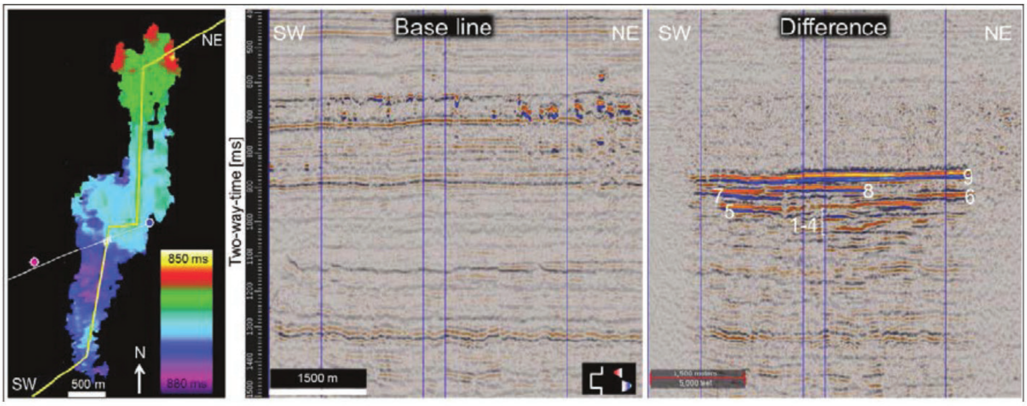

FIGURE 7.4 Seismic image at Sleipner showing the location of the CO_2 plume, its containment below the seal and an interpreted "map" of the location of the plume in the topmost layer below the seal. SOURCE: Furre et al., 2017.

track migration of the plume (Strandli and Benson, 2013; Strandli et al., 2014). Pressure changes measured above the storage reservoir are a highly sensitive indicator of leakage into overlying aquifers (Kim and Hosseini, 2014; Meckel et al., 2013).

Geomechanical responses associated with the pressure buildup caused by CO_2 injection have been successfully monitored using interferometric synthetic aperture radar (InSAR) satellite images to detect land surface deformation. This technique was first used at the In Salah Field in Algeria, where cm-scale uplift was detected and used to infer the presence of a fault in the seal (Vasco et al., 2010). Application of this technique is best suited to regions where the land surface cover does not change much over the year.

Over the past decade, evidence has linked seismic events to underground injection of oilfield brine disposal and, to a lesser extent, hydraulic fracturing of shales for oil and gas recovery (Ellsworth, 2013; Langenbruch and Zoback, 2016; Walsh and Zoback, 2015). Most of these events are not felt at the surface but can be detected either with surface arrays of geophones or with buried geophones. Seismic events induced by pressure increases due to CO_2 injection need to be monitored to provide assurance that they do not present a hazard to structures, people, or the integrity of the reservoir seal. Table 7.1 summarizes information about microseismic events associated with geological sequestration and EOR projects. It is important to note that none of the

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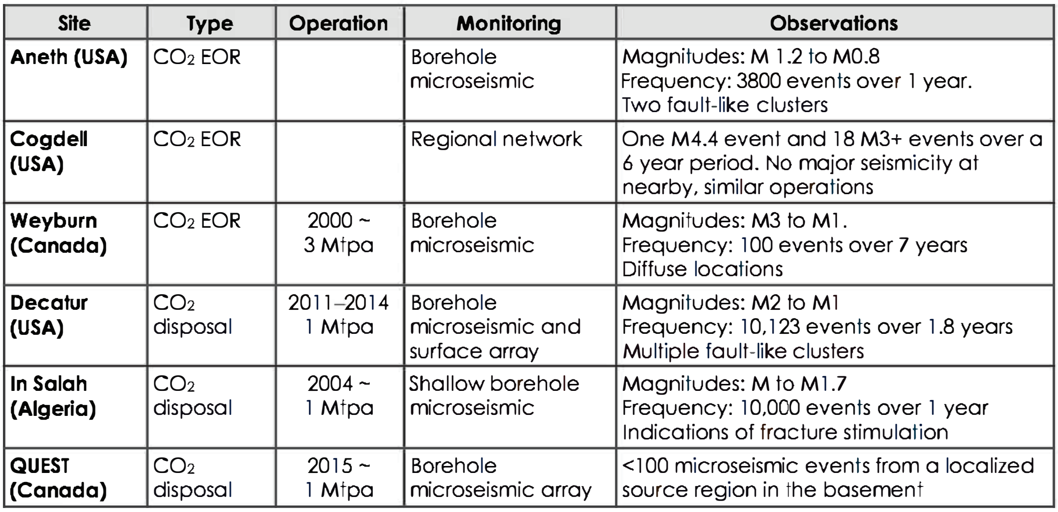
modeling that accounts for the physical and chemical properties of all phases of the injected CO_2 stream and displaced fluids, and is based on available site characterization, monitoring, and operational data (EPA, 2013).

events has been felt at the surface and require sensitive instrumentation to detect and locate them. As shown in the table, most microseismic events are smaller than M2 and are measured most reliably with borehole arrays of geophones. Multiple geophones are needed to locate the origin of the microseismic event.

Monitoring methods are also available for detecting leakage of CO_2 to the surface. Many of these techniques are borrowed from ecosystem sciences that study carbon cycling in terrestrial environments such as eddy-covariance towers (Lewicki et al., 2010), flux accumulation chambers, cavity ring-down spectrometers for measuring ^{13}C and ^{12}C isotopes from mobile or stationary platforms (Krevor et al., 2010), open-path lidar detection systems, soil-gas sampling (Fessenden et al., 2010) and hyperspectral imaging of vegetative stress from airborne and stationary platforms (Male et al., 2010; Rouse et al., 2010). In addition, infrared detectors are widely available for detecting and measuring CO_2 in air and are commonly used for ensuring safe operations around CO_2 sources. The ZERT experiment in Montana showed that leaks of 100 kg/day distributed over an area of 500 m^2 could be detected with a variety of methods described above (Spangler et al., 2010).

Groundwater monitoring can also be used to detect leaking CO_2. Field experiments have employed several approaches for monitoring CO_2 directly, or indirectly in

TABLE 7.1 Microseismic Events Measured at Sites with CO_2 Injection for Sequestration or EOR (from).



Site	Type	Operation	Monitoring	Observations
Aneth (USA)	CO_2 EOR		Borehole microseismic	Magnitudes: M 1.2 to M0.8 Frequency: 3800 events over 1 year. Two fault-like clusters
Cogdell (USA)	CO_2 EOR		Regional network	One M4.4 event and 18 M3+ events over a 6 year period. No major seismicity at nearby, similar operations
Weyburn (Canada)	CO_2 EOR	2000 ~ 3 Mtpa	Borehole microseismic	Magnitudes: M3 to M1. Frequency: 100 events over 7 years Diffuse locations
Decatur (USA)	CO_2 disposal	2011–2014 1 Mtpa	Borehole microseismic and surface array	Magnitudes: M2 to M1 Frequency: 10,123 events over 1.8 years Multiple fault-like clusters
In Salah (Algeria)	CO_2 disposal	2004 ~ 1 Mtpa	Shallow borehole microseismic	Magnitudes: M to M1.7 Frequency: 10,000 events over 1 year Indications of fracture stimulation
QUEST (Canada)	CO_2 disposal	2015 ~ 1 Mtpa	Borehole microseismic array	<100 microseismic events from a localized source region in the basement

SOURCE: DOE, 2017c.

groundwater from reaction products (Anderson et al., 2017; Hovorka et al., 2006; Jenkins et al., 2012; Romanak et al., 2012; Yang et al., 2013). New sampling methods have been developed to get pressurized samples that are representative of the subsurface conditions (Freifeld et al., 2005). Tracers have also been used to track movement of water and/or dissolved CO_2, including perflurocarbons and fluorescein (Kharaka et al., 2009; Ringrose et al., 2009; Würdemann et al., 2010). Because of the high-cost and labor-intensive nature of fluid sampling and analysis, geochemical analyses have been used primarily as research tools.

Expectations and Requirements for Reliable Sequestration in Sedimentary Rocks

Experience with CO_2 sequestration in sedimentary rocks has been consistent with expert opinion first synthesized in the Intergovernmental Panel on Climate Change Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005, p. 12):

> With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological sequestration would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas.

As summarized in Table 7.2, underpinning this statement are a number requirements that should be met to assure secure and reliable sequestration (Benson et al., 2005, 2012; de Coninck and Benson, 2014).

EXPERIENCE WITH SEQUESTRATION IN DEEP SEDIMENTARY ROCKS

Injection of CO_2 into sedimentary rocks began in the 1970s, largely for enhanced oil recovery. However, the Sleipner Saline Aquifer Storage Project set the stage for sequestering anthropogenic CO_2 for greenhouse gas mitigation. The Sleipner Project has sequestered approximately 1 million tonnes of CO_2 per year since 1996 in an off-shore formation at a depth of 800-1,000 m below sea level (Furre et al., 2017). The project has demonstrated that commercial-scale quantities of CO_2 could be securely sequestered in a permeable sandstone formation beneath a low permeability shale seal. It has also provided a wealth of experience and data to advance our understanding about migration of CO_2 in the subsurface and the use of seismic imaging to track migration of the plume.

Including the Sleipner Project, there have been five commercial-scale sequestration projects in saline aquifers (Table 7.3). Four are operating successfully today,

TABLE 7.2 Requirements for Secure and Reliable Sequestration of Supercritical CO_2 in Sedimentary Rocks

Requirement	**Goals**
Fundamental storage and leakage mechanisms	Solid scientific understanding and predictive ability for multiphase flow, interfacial processes, rock-water-CO_2 reactions, secondary trapping mechanisms, pressure buildup, and sealing processes. Multiphysics, multiscale modeling of coupled processes on all timescales up to millennia.
Site characterization, site selection, and risk assessment.	Geological, hydrogeological, geomechanical, and geochemical characterization. Assessment of sequestration capacity, sealing potential, and environmental risks to groundwater, natural resources, and people.
Storage engineering	Design of injection operations, pressure management, plume containment, and acceleration of secondary trapping.
Safe operations	Application of best practices and conduct of operations to minimize risks of worker injury, uncontrolled releases of CO_2, and fugitive emissions.
Monitoring	Monitoring to track migration of the plume, leakage into groundwater, and leakage to the atmosphere; assure well integrity, control pressure buildup, avoid ecosystem impacts, and ensure public safety.
Contingency planning and remediation	Actions planned and executed in the event of unintended releases of CO_2 to the atmosphere or leakage into groundwater, and to control public hazards.
Regulatory oversight	Effective government oversight of projects to ensure due diligence and accountability in all aspects of a CO_2 sequestration project.
Financial responsibility	Shared risk pool with financial set-asides to ensure the adequacy of financial resources in the event that remediation is needed after projects are shut down.
Public engagement and support	Effective communication, consultation, and support from the communities living in the vicinity of CO_2 sequestration projects.

TABLE 7.3 Large-scale Projects to Sequester CO_2 in Saline Aquifers

Project	Location	Date	CO_2 Quantity
Sleipner	Offshore Norway	1996-present	1 Mt/y
In Salah	Algeria	2004-2010	0.7 Mt/y
Snohvit	Offshore Norway	2008-present	1 Mt/y
Decatur	Illinois, United States	2011-2014 2017-present	0.3 Mt/y 1 Mt/y
Quest	Alberta, Canada	2015-present	1.2 Mt/y
Gorgon	Western Australia	?	3.4 Mt/y

SOURCE: GCCSI, 2017.

sequestering a total of 4.2 Mt/y. The Gorgon Project in Northwest Australia will be the largest saline aquifer sequestration project and is expected to sequester from 3-4 Mt/y and to begin operations shortly (Flett et al., 2009). Injectivity has been inadequate at two of the projects: In Salah and Snohvit (Eiken et al., 2011). The In Salah Project was suspended because of the large pressure buildup during CO_2 injection and the associated occurrence of unexpected geomechanical deformation (Eiken et al., 2011; Rutqvist et al., 2010; Vasco et al., 2010). Poor injectivity at the Snohvit field was remedied by injecting into a different interval.

In addition, 125 CO_2-EOR projects in the United States are injecting Mt/y of CO_2 into depleting oil reservoirs (EPA, 2016a). About 21 Mt/y of the CO_2 is captured from anthropogenic sources (EPA, 2016a). allowing for its efficient extraction from the reservoir. Some fraction of the injected CO_2 is produced back with the CO_2, but is immediately separated, recompressed, and injected back underground. Unless the injected CO_2 is intentionally removed from the reservoir after the EOR project is completed, nearly all of the CO_2 injected into the reservoir over the lifetime of the project will remain underground. In the United States alone, 100 billion barrels of oil are technically recoverable with CO_2-EOR (Kuuskraa, 2013), not including residual oil zone production. At the industry-standard ratio of about 3 barrels of oil per ton of CO_2, this corresponds to about 30 Gt of CO_2 that could be sequestered in depleted oil reservoirs (IEA, 2015a; Kuuskraa, 2013). Using advanced CO_2-EOR, which is designed to co-optimize CO_2 sequestration and EOR, the ratio of CO_2 injected to oil produced could be tripled or more, leading to a sequestration potential of greater than 90 Gt CO_2.

IMPACT POTENTIAL

Sequestration Capacity and Footprint in Sedimentary Basins

Global sequestration capacity estimates for sedimentary formations range from several thousand to more than 25,000 Gt CO_2 (Benson et al., 2005, 2012). Due to the enormity of these estimates, more salient issues are the geographical distribution and co-location of potential sequestration sites with large emission sources as well as the potential rate at which CO_2 can be sequestered. If CO_2 is captured from concentrated sources, having nearby reservoirs to sequester the CO_2 is desirable to avoid the complications and costs of long-distance transport. Thus, investable storage reserves may be a fraction of these overall assessment, and factors such as a transport distance may have implications for which locations are prioritized for development. Figure 7.5 shows the location of sedimentary basins that are highly prospective (dark gray) and prospective (medium gray) for CO_2 sequestration. One of the major benefits of direct air capture is that CO_2 can be captured near the best sequestration sites to take full advantage of all the available capacity, thus avoiding limitations associated with co-location with large emission sources.

In the United States, both DOE and the U.S. Geological Survey (USGS) have made estimates of the CO_2 sequestration resource in sedimentary basins. USGS used a geology-based probabilistic assessment methodology to obtain a mean estimate of approximately 3,000 Gt of subsurface CO_2 sequestration capacity that is technically accessible below on-shore areas and state waters (U.S. Geological Survey, 2013). This amount is more than 500 times the 2011 annual U.S. energy-related CO_2 emissions of 5.5 Gt. DOE provides a range of 2,600-22,000 Gt CO_2 based on methods similar to those used by USGS (DOE, 2015b).

Although much work has been done to produce a globally harmonized assessment of the capacity available for geological sequestration, many uncertainties remain about how much of the pore space identified in these assessments will actually be usable (Bachu, 2015). Pressure buildup and associated risks is one of the major constraints on the sequestration capacity (Birkholzer et al., 2009). Some have argued for this reason that the capacity will be on the low end of this range (Ehlig-Economides and Economides, 2010; Zoback and Gorelick, 2012). The extent to which pressure buildup limits sequestration capacity is captured by the concept of a dynamic capacity that is constrained by the maximum rate of injection that will avoid excessive pressure buildup in a geological formation. Dynamic capacity is site and context specific (e.g., Are others also using the formation for sequestration?) and will depend on whether active pressure management (e.g., brine extraction to offset the pressure buildup caused by CO_2 injection) is

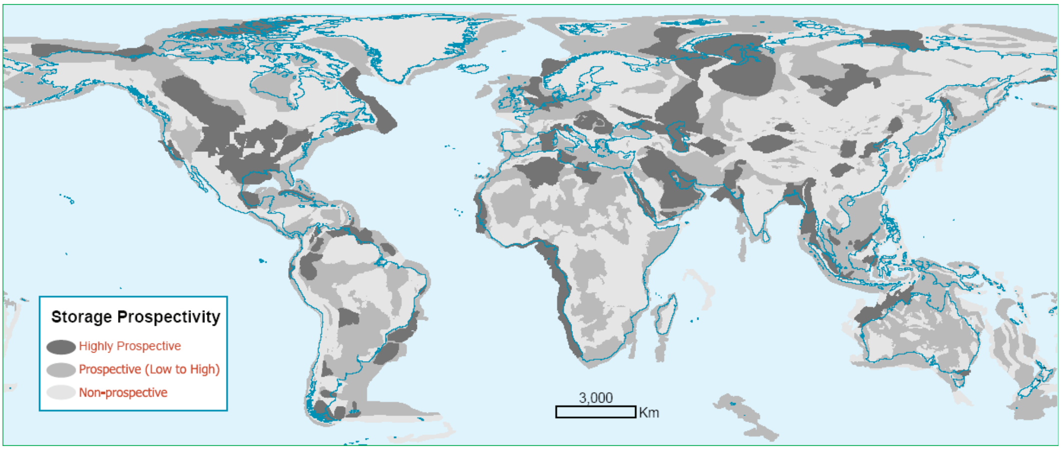


FIGURE 7.5 Location of sedimentary basins that are highly prospective for geological sequestration of CO_2. SOURCE: Bradshaw and Dance, 2005.

implemented (Buscheck et al., 2012). Only when many more commercial-scale projects are implemented will we be able to refine these estimates and gain confidence in the extent to which these sequestration resources can be realized.

The footprint per ton of CO_2 for a sequestration project is highly site specific, depending on the architecture of the storage formation and seal, petrophysical properties of the rocks, pressure and temperature of the storage formation, and extent of secondary trapping. For example, footprint estimates for Sleipner are about 1-3 t/m^2 (Furre et al., 2017). For thinner storage reservoirs, it could be significantly less. A reasonable range for a wide variety of sequestration sites is about 0.5 to 5.0 t/m^2.

Making the decision about whether a particular prospective site is suitable for an actual project requires matching site attributes of the sequestration formation to proposed emissions sources. That is, a sequestration formation with a static capacity of 5 Gt, for example, offers limited guidance in a carbon capture and sequestration (CCS) investment decision. Investors in CCS need confidence that a sequestration reservoir can accommodate, for example, 20 Mt/y for 25 years with an acceptable level of risk around permanence, cost, and license to operate. A range of technical and nontechnical risks and uncertainties serve to limit estimates of investable storage reserves (as compared to static assessments) including the following:

- Containment: Validation of seal and absence of faults;
- Unit Characterization Cost: Access, exploration, and appraisal capability and costs;

- Unit Storage Cost: Mainly well cost and count, which depends on initial injectivity and decline rates; and measuring, monitoring, and verification (MMV)
- End-of-Life Closure and Abandonment: Technical standards, ongoing MMV requirements, and relinquishment of liabilities.

The risks are basin, play, and jurisdictionally independent, and so methods and recommendations for practice may vary depending on the setting.

De-risking and proving-up storage reserves requires traditional exploration, appraisal, and field development planning activities, which are the domain of oil and gas operators and service companies. Such activities include drilling and seismic and extended well tests and require significant time (several years) and costs in excess of $100M to complete a single project. Close cooperation and engagement of the oil and gas industry and service providers will provide valuable guidance and advice for research in this area. That guidance should extend to developing a view on the efficacy of current estimates of geo-sequestration resources/reserves.

COST OF SEQUESTRATION IN DEEP SEDIMENTARY BASINS

Costs for CO_2 sequestration in sedimentary rocks have been estimated based on experience with the projects described above, together with model estimates from scenario-based assessments. Estimates range from \$1 to \$18/tCO_2 (2013 dollars; Table 7.4). The most recent estimates from DOE narrow the range to \$7 to \$13/tCO_2 in the United States. The wide range reflects the highly site-specific nature of geologic sequestration projects. Primary variables include the depth of the formation, number of injection wells required, existing land uses, and ease of deploying monitoring programs. Appendix F provides additional information about costs of compression, drilling and completing injection wells, and pipeline transportation.

The cost estimates in Table 7.4 include well drilling, injection, monitoring, maintenance, reporting, land acquisition and permits, and other incidental costs. They do not include costs associated with remediation activities, which may be required in the case of well leakage, groundwater contamination, or management of the risks of induced seismicity with active pressure management (Brunner and Neele, 2017; Kuuskraa, 2009; Zahasky and Benson, 2016). Proper design and operations should avoid these complications; therefore, costs associated with remediation are not included here.

TABLE 7.4 Compilation of All-In Costs for Sequestration in Deep Sedimentary Basins

Study	Low Estimate (2013\$/tCO_2)	High Estimate (2013\$/tCO_2)
IPCC, 2005	1	12
ZEP, 2011	2	18
DOE, 2014	7	13
GCCSI, 2011	6	13

NOTE: These estimates do not include the cost of compression (Appendix F).
SOURCE: Rubin et al., 2015.

REGULATIONS, BEST PRACTICES, AND STANDARDS

In the United States, each year more than 2.5 Gt of brines are injected into deep underground formations for disposal (EPA, 2018). This experience underpins a substantial body of work on technical, administrative, and regulatory approaches for achieving secure and reliable sequestration of supercritical CO_2 in sedimentary basins. The United States has developed regulations for CO_2 sequestration in saline aquifers, covering issues such as siting, well construction, monitoring, and risk management, particularly with regard to the presence of active or abandoned wells in the so-called area of review (EPA, 2010). Injection into oilfields is regulated under a different set of requirements (EPA, 2018). These regulations are promulgated through the U.S. Environmental Protection Agency's (EPA's) Underground Injection Control Program, which is intended to protect freshwater resources.

International guidelines for tracking and reporting greenhouse gas emissions have been developed for inventory accounting of CO_2 capture and sequestration projects (IPCC, 2006). In addition, the International Organization for Standards has developed standards for activities related to CO_2 capture, transportation, and geologic sequestration, including the design, construction, and operation of the project; monitoring and verification; environmental planning and management; and risk management (ISO/TC 265, 2011). Finally, DOE has developed best practice manuals. covering site screening, selection, and characterization (DOE, 2017d); public monitoring, verification, and accounting (DOE, 2017g); outreach and education (DOE, 2017b); operations (DOE, 2017f); risk management and simulation (DOE, 2017e); and storage formation classification (DOE, 2010). These regulatory approaches and practices are likely to evolve as experience grows with the implementation of new commercial projects.

Although much has been done to develop the legal and regulatory framework for CCS (Dixon et al., 2015), several challenges and unresolved issues remain regarding the regulatory and legal framework for CO_2 sequestration in deep geological formations, including the following:

Financial responsibility for long term liability: CO_2 sequestered in deep geological formations is expected to persist in a supercritical phase for hundreds to thousands of years or longer. Although the risks of leakage or other environmental harm are expected to decrease over time because of the secondary trapping mechanisms and pressure decreases in the post-project period, the possibility nevertheless remains that some CO_2 could leak out of the reservoir. After the project has been shut down, who is responsible for monitoring and remediation, for how long, and with what mechanism? Although proposed as solutions to this issues, bonds, shared risk pools, and insurance have not matured because of the early stage of this technology (e.g. Gerard and Wilson, 2009). This issue is less salient in parts of the world where the subsurface is "owned" by the government, which will assume responsibility after assurances have been provided that the CO_2 is expected to remain trapped. Lack of clarity on this issue is one of the largest barriers to scale-up of CO_2 sequestration in deep geological formations (Davies et al., 2013).

Pore space ownership: Who can grant the right to sequester CO_2 in subsurface pore space depends on national and sub-national laws defining mineral rights, water rights, surface rights, and other beneficial land uses. Clarification of rights where conflict might exist is needed to expedite scale-up of CO_2 sequestration. The large footprints of full-scale CO_2 sequestration projects, which can potentially extend over 100 km^2 or more, present additional complications. Aggregating access to the subsurface from 10s to hundreds of landowners can be timing consuming and expensive. When landowners desire to use their pore space for sequestration, or if people do not support the project, legal measures used by the oil and gas industry, such as unitization (management of adjacent properties under a common operating regime) may be necessary, and the rules for doing so vary by state.

Regulatory impediments: As expected when new regulatory requirements are promulgated, some requirements are too challenging or too expensive for operators. Examples include overly prescriptive monitoring programs that do not provide the operator with the flexibility to tailor the monitoring program to site-specific attributes; rules for transitioning from a CO_2-EOR project to a sequestration project; and state-based requirements that conflict with national requirements.

Over time, none of these issues is insurmountable, as evidenced by practices in more mature mineral and resource extraction activities. However, maintaining a science-based approach to assessing risks, managing risks, and updating regulations will be essential to support Gt-scale deployment of this technology.

RESEARCH AGENDA

Scaling up global CO_2 sequestration in deep sedimentary formations to 5-10 Gt/y CO_2e is an enormous task that requires research to ensure its secure and reliable implementation. To put this into perspective, 5-10 Gt/y sequestration in deep geological formations would require more than a 100-fold scale-up from current sequestration operations and would assume the scale of global oil production, which is a $2 trillion/y industry. The enormous sequestration capacity of geological formations combined with the permanent nature of geological storage warrant a significant investment in research and development (R&D). The more than 100 years of oil and gas operations created a sufficient foundation of knowledge to continue expansion of geological sequestration projects in oil and gas reservoirs and saline aquifers. Scale-up would occur gradually with learning-by-doing as a key component of capacity building and knowledge generation. However, if this technology is to expand to the Gt/y CO_2 scale and beyond, much more intensive use of our sequestration resources will be required, which depends on better information to assess risks, select sites, and provide assurances of their safety and effectiveness. The following 10-year research agenda is designed to develop the scientific and engineering knowledge needed to assess the conditions under which Gt/y CO_2 sequestration in deep geological formations would be possible, as well as best practices for engaging local communities and the general public on geological sequestration.

The key research needs are summarized below, and their costs are listed in Table 7.5. Some of these needs arise from experiences with existing sequestration projects or analogous operations, such as large-scale water injection or natural gas storage. Others arise from our limited ability to predict the outcome of complex coupled multiphysics, multiscale processes on timescales of centuries to millennia. All of these needs are critical to scale sequestration to the Gt/y level.

A large number of new projects is expected to be deployed under the 45Q rule over the coming decade (45Q is a new tax incentive providing $35/t for CO_2-EOR and $50/t for saline aquifer sequestration[2]). This provides an enormous opportunity for the R&D community to partner with industry to gain real-world experience in Mt-scale sequestration. In fact, many of the research needs can only be met through partnership with

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[2] See http://uscode.house.gov/view.xhtml?req=(title:26%20section:45Q%20edition:prelim) (accessed January 28, 2019).

industry, which facilitate the leveraging of the large investments in site characterization and infrastructure that will take place and the two-way transfer of knowledge in the context of real-world projects.

These research needs, although largely framed in the context of the United States, relate to valuable fundamental knowledge that can be transferred to regions around the world through international collaborations.

Many of these research topics have been supported during the past decade, to one degree or another, by DOE, the Department of the Interior (DOI), EPA, and the National Science Foundation (NSF). Significant progress has been made to support sequestration of emissions resulting from the use of fossil fuel sources in electricity generation and industrial processes. This research agenda is designed either to supplement existing programs or to place a stronger emphasis on certain topics than currently exists. The needs arise when considering prospects for multi-Gt-CO_2/y negative emissions over many decades, and perhaps a century or more. Negative emissions with sequestration in deep geological formations presents unique challenges because (1) CO_2 may be sequestered in regions lacking large emission sources, that is, regions that have not been the focus of current investigations and (2) the use of deep geological formations on a large scale for the purpose of negative emissions may double or triple (or more) the total amount of geological sequestration. This massive scale-up in geological sequestration will require more intense resource utilization and development of new sequestration resources that may rely on advanced reservoir engineering practices that remain in their infancy, such as accelerated secondary trapping mechanisms and reservoir pressure management. These activities will support net emissions as well as sequestration from fossil fuel sources.

1. Quantifying and managing the risks of induced seismicity. During the past 5 years an unprecedented number of induced seismic events have occurred in regions with historically low rates of seismicity, largely in the midwestern United States. Notably, Oklahoma experienced a rapid increase in the number and magnitude of earthquakes (Walsh and Zoback, 2015). These events have been attributed primarily to the disposal of oilfield brines into saline aquifers (Keranen et al., 2014), which increases the pore pressure and sometimes causes critically stressed faults to slip. The injection of brine into aquifers directly above fractured basement rocks has resulted in the most and largest earthquakes. A small number of induced earthquakes have been attributed to hydraulic fracturing (Ellsworth, 2013). Although most events are very small, some are large enough to be a nuisance, and at worst, capable of property damage and harm to people. Some argue that sequestration in deep saline formations poses similar risk because of the widespread pressure buildup associated with injection of large volumes of CO_2 at high rates (Zoback and Gorelick, 2012). Information and knowledge are not sufficient to distinguish low-risk from high-risk sites, particularly for sequestration in saline aquifer directly over basement rock. Susceptibility to induced seismic events ranges over two orders of magnitude for slip along basement faults, and current knowledge gaps prevent prediction of those areas susceptible to induced seismic events. In addition, while many sites have experienced a large number of micro-seismic (not felt at the surface) events because of CO_2 injection, whether these indicate the potential for larger events is uncertain. Research is needed to understand better the mechanisms, risks, and consequences of pressurization-induced slip and associated seismicity along pre-existing fractures in basement rocks. In addition, field testing techniques are needed to quantify risks in advance of sequestration site selection. For example, pressure transients measured during fluid injection are routinely used to measure the permeability of formations. Similar tests could be used to address susceptibility to induced seismic events. This information can be used to develop a methodology for selecting sites with low risk and/or to manage injection rates to limit the potential to induce seismic events.

Earthquakes have been induced at some CO_2 sequestration sites, notably the In Salah Project in Algeria and the Decatur Project in Illinois. These events have been small (< ~M 1) and not felt at the surface or caused any damage. Other sequestration projects have not induced any detected seismic events, even when injecting into basal aquifers above a crystalline basement rock. The potential for harmful earthquakes and the extent to which cautionary exclusion of some locations will affect estimates of sequestration capacity need to be evaluated. Specific research directions include the following:

- Understanding why some CO_2 sequestration sites experience induced earthquakes and other do not;
- Determining the potential for pre-qualifying sites to avoid induced events using the best available models and data;
- Developing short-term tests to assess the risks of induced earthquakes before committing to a project;
- Understanding the implications of induced seismicity on sequestration capacity estimates and injectivity rates;
- Developing mitigation approaches for minimizing risks, such as brine extraction, injection pressure management, or requiring both a top and bottom seal; and
- Understanding the potential for fault slip to increase leakage from the sequestration reservoir.

TABLE 7.5 Costs and Components for a Geologic Sequestration Research Agenda

	Recommended Research	Estimated Research Budget ($M/y)	Time Frame (years)	Justification
Basic Research/Development	Reducing seismic risk	50	10	The proposed budget would allow for 3 experiments in different U.S. regions, each at a cost of about $15M/y for 10 years. The region-specific projects would be supported by $5M/y of model development, laboratory studies, and analysis of new and existing data sets. This research would improve understanding of and reduce the risks of induced seismicity at geological sequestration sites, develop methods for assessing and mitigating risks of seismicity, improve capacity estimates by screening sites that are high risk for induced seismicity, and help quantify the risk of leakage from fault slippage.
	Improving secondary trapping prediction and methods to accelerate secondary trapping	25	10	This research program would support a 10-y multi-investigator team to perform a large-scale experiment designed to quantify the effectiveness of natural and accelerated trapping for immobilizing CO_2 in the post-injection period. The experiment would require a combination of field experiments, multiscale laboratory experiments, numerical modeling, and monitoring. The goals of this coordinated program would be to improve understanding of the coupled, multiscale, multiphysics processes governing secondary trapping, reliably predict and verify their effectiveness, and develop and demonstrate methods to accelerate secondary trapping of CO_2.
	Improving simulation models for performance prediction and confirmation.	10	10	This program would support 2-3 teams of researchers to develop improved simulation models for predicting the fate and transport of CO_2 in the subsurface, particularly with regard to the effects of geological heterogeneity, secondary trapping mechanisms, geochemical reactions, geomechanical responses to CO_2 injection, and the coupling between them over thousands of years. Simulation models will be built at a hierarchy of relevant scales, from the nano-scale to the basin-scale. Robust approaches for translating between these scales will be developed to ensure that reservoir and larger scale models incorporate accurately the range of relevant physical processes influencing plume migration during injection operations and the post-injection period.

continued

TABLE 7.5 Continued

	Recommended Research	Estimated Research Budget ($M/y)	Time Frame (years)	Justification
Development/Demonstration	Increasing the efficiency and accuracy of site characterization and selection	45	10	Partner with industry to develop and test innovative approaches for characterizing greenfield sites, which usually require about $100M to assess the suitability of a site. The program could be carried out by expanding the CarbonSAFE program to include 2 sites with sequestration quantities of 200+ Mt CO_2 to assist states and commercial entities in qualifying sites for large-scale deployment (4 projects over a 10-y period). The data collected from this program should be made publicly available through NETL's EDX platform, USGS, and university data archives, and federated data volumes such as NatCarb. This program would develop the knowledge needed to develop and demonstrate the following: efficient and effective methods for characterizing geological sequestration sites over the large footprint of a commercial-scale CO_2 sequestration project (~100 km^2), methods for identifying and characterizing faults in seals and basement rocks; and methods of characterizing geological heterogeneity and associated trapping of CO_2. $5 M/y of the proposed budget would be used to support academic, laboratory, and industrial research developing innovative approaches that could be tested in the above-mentioned field programs.
	Improving monitoring and lowering costs for monitoring and verification.	50	10	Many new sequestration projects are likely to be developed over the next 10 years as a result of the 45Q rule. These projects provide an ideal opportunity to partner with industry to develop, test, and deploy the next generation of integrated monitoring systems for commercial projects. The proposed research program would provide for 4-6 projects at a cost of $5-10M/y. The collaborative projects would develop and demonstrate approaches to optimize integrated monitoring programs that reduce costs while increasing quality and access to real-time information about the status of stored CO_2. In addition to the field experiments, $10 M/y would be used to support fundamental research to develop and test new approaches to quantify mass balances, measure CO_2 saturations, and quantify leakage.

	Developing reservoir engineering approaches for co-optimizing CO_2-EOR and sequestration	50	10	Develop and demonstrate reservoir management practices to co-optimize CO_2-EOR and CO_2 sequestration to achieve negative emissions during oilfield operations. Quantify the extent of negative emissions that can be achieved by co-optimization. Two field-scale experiments in partnership with industry are proposed, each with a budget of $20 M/y for 10 years. $10 M/y will support academic, national laboratory, and industry research to develop new approaches for co-optimization.
Deployment	Assessing and managing risk in compromised sequestration systems.	20	10	Improve understanding of the impact of leakage on groundwater systems and the vadose zone. Quantify the extent to which these interactions attenuate CO_2 migration and mitigate risks of leakage to the atmosphere.
	Social sciences research to improve public engagement effectiveness with local communities and the general public	1	10	Establish best practice for community engagement, rules of practice, and regulation guidelines. Provide educational materials for increasing awareness of the need, opportunity, risks, and benefits of geological sequestration for negative emissions.

2. Increasing the effectiveness of site characterization and selection methods. Site characterization and selection is arguably the single-most important factor for secure and reliable CO_2 sequestration in sedimentary rocks, but it poses challenges beyond what is required for oil and gas exploration and production. Research needs associated with the scale-up of commercial sequestration projects include the following:

- Developing and demonstrating efficient and effective methods for characterizing the reservoir and seal. The area requiring characterization and assessment for a 50-100 Mt scale sequestration site can be about 100 km^2, which is large compared to even large oil and gas fields. This work should be performed in collaboration with industry, as long as all data will be made available to the public.
- Identifying small faults in the seal that may provide leakage pathways if they are permeable. Such faults are difficult to resolve from seismic imaging. Experience from In Salah and other reservoirs has shown that small faults, often called sub-seismic, are not revealed by conventional analysis. In this case, unexpectedly rapid transport through the reservoir and unusual geomechanical uplift highlighted the presence of fractures. Better methods for detecting faults with small offsets are needed. Improved methods for seismic data acquisition and processing together with field experiments in collaboration with industry are also needed.
- Imaging faults in igneous and metamorphic basement rocks that may create risks for induced seismicity. Such faults are rarely imaged because seismic data sets are optimized to provide the highest possible resolution in overlying resource-bearing sedimentary formations. Moreover, base fault detection is challenged by the near vertical nature of the faults together with the lack of stratigraphic markers that support detection of faults in sedimentary rocks. Reanalysis of existing data sets to identify basement faults, together with acquisition of new data sets that are optimized for basement fault detection, would help to develop the methodology for basement fault detection. The work could be done in collaboration with industry because a large amount of useful data already exists but is currently inaccessible.
- Obtaining reliable information on geological heterogeneity in the reservoir, which has significant effects on secondary trapping mechanisms and may be an important part of the security case for sequestration.
- Developing publicly available data sets that can be used by the research community and private developers interested in sequestration projects.

- Expanding on programs such as CarbonSAFE[3] to incorporate highly prospective sequestration sites where bioenergy carbon capture and sequestration (BECCS) and direct air capture are the likely sources of CO_2.

3. Improving monitoring and lowering costs for monitoring and verification. Monitoring is critical for determining whether a project is performing as designed. Over the past 20 years, impressive progress has been made to adapt and demonstrate component technologies to track plume migration and detect leakage, land surface deformation, pressure buildup, rock-water-CO_2 reactions, and other factors. Important gaps remain, however, in several areas that will be essential to large-scale deployment of sequestration in geological formations:

- Mathematical approaches are needed for co-inversion of multiple data sets coupled to performance prediction models to provide more information than is available from one data set alone. For example, it is very difficult to measure the CO_2 saturation distribution in a plume with seismic data alone, but co-inversion of seismic data with electrical resistance tomography data using a 3-D reservoir model may provide detailed information about saturation distributions.
- Current monitoring methods can identify the location of CO_2 in the storage reservoir and detect leakage. However, they could be improved with more quantitative information about CO_2 saturations and mass balances. This information can calibrate and validate the simulation models that are used for a variety of purposes, including resource optimization, forecasts of plume migration during the post-injection period, and regulatory compliance.
- Strategies and technologies are needed for an adaptive monitoring program that is site-specific and responsive to the changing needs and conditions of the sequestration projects. Fit-for-purpose approaches with sufficient flexibility to respond to the evolving understanding of project's uncertainties and risks are needed.
- Today, seismic monitoring is the primary method used to track the location of sequestered CO_2. Surveys are labor intensive, time consuming, and expensive and therefore conducted at multiyear intervals. Alternative methods to deploy

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[3] The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative projects focus on development of geologic storage sites for the storage of 50+ million metric tons (MMT) of CO2 from industrial sources. CarbonSAFE projects will improve understanding of project screening, site selection, characterization, and baseline monitoring, verification, accounting (MVA), and assessment procedures, as well as the information necessary to submit appropriate permits and design injection and monitoring strategies for commercial-scale projects. These efforts will contribute to the development of 50+ MMT storage sites in anticipation of injection by 2026.

seismic imaging that allows continuous acquisition and real-time analysis in combination with subsurface pressure data can enable rapid leak detection and response.

- Advanced methods for locating and characterizing leaks, should they occur, are needed to guide remediation and compliance efforts.

4. Improving confidence in secondary trapping mechanisms and accelerating their trapping speed. Secondary trapping mechanisms can be viewed as an insurance policy for geological sequestration of CO_2. "Secondary" does not imply that these mechanisms are of secondary importance, only that they serve backup if the wells are leaky or the seal does not perform as expected. The benefits of secondary trapping mechanisms, such as solubility trapping, residual gas trapping, and mineral trapping, compensate for flaws in either the seal or in the leakage pathways created by wells penetrating the seal above the sequestration reservoir (see "Geological Requirements for Secure and Reliable Sequestration" above). For many reservoirs, the risks for leakage are low, and therefore secondary trapping mechanisms are not important. For others, secondary trapping may be the factor that ensure the reservoir's suitability for sequestration. When secondary trapping mechanisms are an important part of sequestrtion security, it will be necessary to improve understanding of how they work and how to accelerate them. Research is needed to improve understanding of the coupled, multiscale, multiphysics processes governing secondary trapping, and to reliably predict and verify their effectiveness. For example, it is not yet possible to accurately simulate convection-driven dissolution of nearly all of the injected CO_2 over the 1,000s of years during the post-injection period. Some research simulators are starting to tackle the problem, but commercial simulators have neither sufficiently high spatial resolution nor the advanced numerics needed to simulate this reliably (Riaz et al., 2006). Similarly, the Land trapping model was developed for application in the context of waterflooding oil reservoirs (Land, 1968). Because CO_2 is soluble in water, Ostwald Ripening has the potential to redistribute the residually trapped CO_2, potentially leading to remobilization of the gas (de Chalendar et al., 2018). This phenomenon is not captured in the Land trapping model or any other trapping model available in commercial simulators today. Similarly, no models can accurately simulate the coupling between solubility trapping and residual gas trapping, changes in wettability caused by mineral precipitation or dissolution and consequent redistribution of the CO_2, and the millennial-scale evolution of a plume of CO_2 subject to these processes.

In addition, a little-explored area of research is the opportunity to accelerate secondary trapping of CO_2. This acceleration would limit the footprint of the CO_2 plume, shorten the period over which leaks could occur, reduce the amount of CO_2 that would leak in the case of leaking wells and poor-quality seals, and reduce the need for risk management activities, such as monitoring and maintenance of contingency plans.

This research activity would require a combination of theory, simulation, and laboratory and field experiments.

5. Developing reservoir engineering approaches for co-optimizing CO_2-EOR and sequestration. Sequestering CO_2 in oil and gas reservoirs has the potential to be a carbon neutral or carbon negative activity, while simultaneously producing hydrocarbons that can be used for applications that are difficult to decarbonize (e.g., air transport). Moreover, oil and gas reservoirs have both a seal that demonstrably retains buoyant gases over long timescales and a reservoir that has been characterized extensively. Current CO_2-EOR projects are designed to maximize profits by minimizing the amount of CO_2 injected into the oil reservoir for every barrel of oil produced. In a world that values CO_2 sequestration, the economic drivers will change to co-optimize revenues from oil production and CO_2 sequestration. For such projects to become carbon negative, they must significantly increase the ratio of CO_2 injected per barrel of oil recovered. Research is needed to develop reservoir engineering methods to co-optimize CO_2 sequestration and enhanced oil recovery because current approaches for CO_2-EOR are not likely to efficiently sequester more CO_2 simply by increasing the amount of CO_2 injection. Increasing the amount of CO_2 injection using today's reservoir engineering approaches for CO_2-EOR will only result in more recycling of CO_2, driving up costs and decreasing efficiency. Alternative approaches such as gravity stable injection scheme using horizontal injection wells could minimize CO_2 recycle and increase oil recovery while increasing the efficiency and amount of sequestration. In addition, conventional CO_2-EOR has been optimized for miscible recovery (oil and CO_2 become a single phase, thus making it easier to produce the oil), which is only possible for deep, light crude oils. Many oil reservoirs are not suitable for miscible recovery because of the oil composition, temperature, or pressure of the reservoir. but still have significant sequestration capacity. Methods for co-optimization of oils that are not miscible with CO_2 are needed. In addition, methods for co-optimizing oil recovery from residual oil and transition zones (i.e., areas with oil saturations that are too low for conventional oil recovery operations such as primary production or water flooding) (Koperna et al., 2006). Opportunities for sequestration and co-optimization also exist in (a) near off-shore formations, which have important infrastructure considerations, (b) stacked formations where one location has several different zones in which CO_2 can be sequestered, and (c) by sequestering CO_2 either in flanks of the reservoir or below main pay zones for pressure support.

6. Assessing and managing risk in compromised sequestration systems. The potential impacts of CO_2 leakage, particularly into freshwater aquifers, must be better understood. Long before CO_2 is leaked into the atmosphere, it migrates upward from the sequestration reservoir toward the land surface. Along the way it will interact with the geological system (e.g., rocks, groundwater, and microbiota) and manmade materials (e.g., casing and cement). These interactions may attenuate leakage into the atmosphere, which is beneficial from a climate-change perspective, but may have negative consequences. In particular, leakage of CO_2 into aquifers reduces the pH of the fluids and changes the geochemical equilibrium. Under certain conditions at some sites, hazardous elements such as arsenic may be mobilized (Zheng et al., 2009). The risks associated with leakage into the subsurface are highly site specific and localized, and although the likely consequences are improbable and negligible, some risk of substantial impacts remains. Consequences will depend on the amount of leakage, composition of the leaked gases (for oil or gas field sequestration, some hydrocarbons may be carried along with the CO_2), and characteristics of the subsurface hydrogeological setting. Research is needed to quantify the likely impacts of leakage for deep, intermediate depth, and shallow aquifers, as well as the vadose zone.

7. Improving simulation models for performance prediction and confirmation. Simulating the multiscale, multiphysics, coupled processes that influence the fate and transport of supercritical CO_2 injected into sedimentary rocks remains a grand challenge that underpins critical aspects of geological sequestration of CO_2. Site selection, storage engineering, risk assessment, and project performance confirmation all rely heavily on the veracity of simulation models. Particularly challenging issues for today's generation of simulation models that are unique to geological sequestration stem from three factors, namely: the very large footprint of a typical sequestration project (100 km^2); the thermodynamic properties of CO_2 which result in a complex coupling between gravitational, buoyant, and viscous forces, along with dissolution in brine and reaction with the rock; and the permanent nature of sequestration, which entails understanding of the behavior of geologically sequestered CO_2 on timescales of 1,000s of year and longer.

These challenges necessitate dealing with geological heterogeneity over very large spatial domains and finding effective ways to volume average rock properties; simulating processes over timescales of centuries to millennia; quantifying uncertainty; and incorporating coupled processes, including diffusive and convective transport, geomechanical deformation and associated risks of induced seismicity, and the kinetics of rock-water-CO_2 reactions. Probabilistic treatments of the subsurface geology are needed to quantify likely outcome and confidence levels. Importantly, reliable methods for incorporating what is learned about secondary trapping processes are needed to predict post-injection performance and support regulatory decisions about important issues such as how long monitoring will be required.

8. Improving community engagement and informing the general public about the need, opportunity, risks, and benefits of CO_2 sequestration in deep geological formations. Several large-scale CCS demonstration projects have been delayed, abandoned, or relocated globally as a result of public opposition or regulatory action. Any research agenda should include a focus on establishing best practices for community engagement, rules of practice, and regulatory guidelines. The general public and policymakers should be educated about the risks and benefits of geological sequestration.

Implementation, Cost, and Management of the Research Agenda

Implementing the research agenda outlined above requires data, community coordination, and funding. Data are the lifeblood of research, but much relevant data are poorly accessible, either because they are scattered in laboratories around the world or because they are proprietary. In particular, the oil and gas industry has collected decades of data on CO_2 injection, sequestration, oil recovery, brine recovery, and other processes. However, only a small fraction of these data is available, and only with restrictions, such as not publishing raw data. Likewise, expertise in laboratory analysis, computational modeling, and monitoring, as well as practical experience with sequestration projects resides in many countries. Yet, it will take a collective effort to understand and develop effective co-optimization techniques for storing CO_2 in sedimentary formations. A virtual data repository would facilitate the necessary data sharing and collaboration.

This budget reflects a substantial increase of the DOE 2017 budget for CO_2 sequestration in deep geological formations (DOE, 2018), as well as the additional and unique needs associated with sequestration for the purposes of negative emissions. This research supports ramping up implementation of CO_2 sequestration in deep sedimentary formations to the 100Mt and then Gt scale over the coming decade. Much of the research agenda requires field experimentation and testing. In most cases, new wells should be drilled and completed at costs of about $5M per well, research infrastructure such as roads and power lines must be built, and CO_2 must be purchased at a cost typically in the order of $100/t. Close partnership with existing or planned industrial projects can help reduce these costs. However, past experience has shown that research activities do not always align with industry schedules and priorities.

DOE, NSF, EPA, and DOI have distinct and important roles to play in pursuing a comprehensive research agenda. In addition, capacity building to support regulatory and land-use decisions would benefit from a coordinated and rigorous multiagency research program. The potential agency contributions to the research needs and data repository are identified in Table 7.6 and summarized below.

Department of Energy: The Office of Science and the Office of Fossil Energy have supported fundamental and applied research on geological sequestration for the past two decades. New research and development needs in DOE's purview include research on trapping mechanisms; multi-scale, multi-physics modeling of the fate and transport of CO_2 in the subsurface; and development of storage engineering approaches that optimize and accelerate trapping, co-optimize hydrocarbon production, reduce the costs of real-time monitoring, assess the risks of induced seismicity, and expedite site characterization and selection.

National Science Foundation: NSF plays an important role in engaging and leveraging university research on Earth processes that are relevant to sequestration. Cutting-edge advances in hydrology, geochemistry, geophysics, biogeochemistry, and social science all have bearing on the efficacy and acceptance of geological sequestration.

TABLE 7.6 U.S. Federal Agency Responsibilities for the Research Needs and Data Repository

Research Need	DOE	NSF	EPA	DOI
Induced seismicity	X	X		X
Characterization and site selection	X		X	X
Monitoring	X			
Accelerated trapping		X		
Co-optimization of EOR/sequestration	X			
Environmental impacts and risk assessment	X		X	
Model development	X	X		
Data repository	X			

In addition, NSF can support translational research, such as bringing the latest innovations to sequestration science and engineering, and can build capacity for industry and regulatory agencies to rapidly scale this technology.

Environmental Protection Agency: EPA regulates the site selection and compliance with operational, monitoring, and reporting requirements, and establishes greenhouse gas inventory accounting requirements for geological sequestration projects. EPA is also concerned with risk and could work with DOE and DOI to support the development of reliable approaches to assess, minimize, and monitor the risk of groundwater contamination at sequestration sites. The agency could also work with DOE to develop monitoring-modeling workflows to reduce the ongoing costs of meeting regulatory requirements.

Department of Interior: USGS conducts research to improve understanding of induced seismicity. In addition, both USGS and Bureau of Land Management (BLM) play important roles in the scale-up of geological sequestration. USGS has assessed geological storage resources in U.S. sedimentary basins (Blondes et al., 2013) and is well placed to identify prospective regions for geological sequestration of CO_2. Continuous updates of USGS estimates on prospective sequestration and resource size using information from real-world experience would support scale-up to Gt/y and would guide site characterization and site selection. Federal lands will be needed to achieve Gt-scale sequestration, BLM could undertake a study of their sequestration potential.

SUMMARY

Tens of millions of tons of CO_2 are injected into subsurface pore space annually, mainly to facilitate enhanced oil recovery. For this reason, it is often taken for granted that the oil industry and its partners can easily provide unlimited CO_2 sequestration when and if it becomes economically viable. However, there is an enormous difference between megaton-scale EOR projects in oil fields and sequestration of billions of tons of CO_2 per year in deep saline aquifers. Implementing the research agenda outlined above will yield information essential for storing enough CO_2 to make a substantial contribution to greenhouse gas mitigation. It will also help project operators to avoid secondary impacts that could harm people and generate opposition to geologic sequestration. Some of the research is aimed at reducing the potential for groundwater contamination above CO_2 reservoirs, even those with otherwise imperceptible leaks. Other research is aimed at reducing the number and size of induced earthquakes or even avoiding them through careful site selection. The proposed program of early-stage laboratory research combined with site-specific research will lay the foundation for scale-up of CO_2 sequestration in deep geological formations to the Gt level.

CHAPTER EIGHT

Synthesis

This chapter synthesizes the impact potential and research agendas for the various negative emissions technologies (NETs). It summarizes the committtee's assessment of the potential rates of CO_2 removal for both the United States and the globe, as well as the costs for the individual NETs. It also combines the research proposals for each NET into an integrated research proposal and a list of research priorities.

The committee repeatedly encountered the view that NETs will primarily be deployed to reduce atmospheric CO_2 after fossil emissions are reduced to near zero. In contrast, because it will likely be very expensive to decrease anthropogenic emissions once they reach low levels, methods for reduced and negative emissions will probably be competitors for an extended period, even during a sustained period of net negative global emissions.

Conclusion 1: Negative emissions technologies are best viewed as a component of the mitigation portfolio, rather than a way to decrease atmospheric concentrations of carbon dioxide only after anthropogenic emissions have been eliminated.

CO_2 IMPACTS

In Chapters 2-7, the committee identified the potential rates of CO_2 removal and sequestration that could be achieved safely and economically, given our current knowledge and level of technological development. "Safe" means that deployment of the NET would, with high confidence, not cause the large adverse societal, economic, and environmental impacts that are described in those chapters and later in this chapter. "Economical" means that deployment would cost[1] less than \$100/t CO_2 (and in some cases less than \$20/t CO_2). As noted earlier in the report, geologic sequestration is an enabling technology and not a NET in and of itself. Including combustion-based bioenergy with carbon capture and sequestration (BECCS) as being ready for large-scale deployment implies that the committee believes that geologic sequestration

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[1] The committee refers to direct costs of attaining negative emissions (e.g., operating costs, labor costs). All NETs have a full set of indirect costs (e.g., impact on land values) that may not be reflected in direct cost estimates.

is ready for large-scale deployment. The following information provides context for these estimated costs of deployment:

- the most recently published EPA estimates of the social cost of carbon are ~\$10/t CO_2 to ~\$100/t CO_2 in 2020 and ~\$25/t CO_2 to ~\$200/t CO_2in 2050, at discount rates of 2.5-5% (EPA, 2016b);
- price of \$19.66/t CO_2 in the European Union carbon market as of July 19, 2018;[2]
- current U.S. tax credit of \$50/t CO_2 for carbon capture and sequestration known as the 45Q rule;[3]
- average 2018 price of ~\$100/t CO_2 under California's Low Carbon Fuels Standard (Aines and Mcoy, 2018);
- ~\$200/t CO_2 combination of the 45Q rule and the recently announced changes in credits under California's Low Carbon Fuels Standard, which would allow fuels made with CO_2 from direct air capture;[4] and
- the carbon price of more than \$1,000/t CO_2 in year 2100 estimated by several integrated assessment models (IAMs) reviewed in the latest IPCC report (IPCC, 2014b).

In addition, \$100/t CO_2 is also approximately equal to \$1/gallon of gasoline, because combustion of a gallon of gasoline releases approximately 10 kg of CO_2.

The committee's assessments of individual NETs and of technologies that sequester CO_2 are presented in Tables 8.1 and 8.2, respectively. The NETs and sequestration approaches in these tables exhibit a wide range of technical maturity. Some approaches to carbon removal, such as reforestation, have been developed over many decades and have already been deployed at large scale. Others, such as several types of enhanced carbon mineralization, are at the early stages of exploration by academic researchers and have never been tried in the field. In general, the cost estimates for technologies that have not been demonstrated are more speculative than those for technologies that have been deployed at scale. However, even NETs that are relatively mature will benefit from additional research to reduce costs and negative impacts and to increase co-benefits.

There are also fundamental differences among the primary factors that limit potential rates and capacities of NETs. Land-based NETs, especially afforestation/reforestation and BECCS, are ultimately constrained by land availability, because of the competing needs to produce food and preserve biodiversity and by the responses of landowners

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[2] See https://www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances#!/2018/07/19 (accessed January 29, 2019).

[3] See https://www.law.cornell.edu/uscode/text/26/45Q (accessed January 29, 2019).

[4] See https://www.arb.ca.gov/fuels/lcfs/lcfs.htm (accessed January 29, 2019).

to incentives. Research on land-based options would help to ensure that the capacities listed in Tables 8.1 and 8.2 can be increased. In contrast, the major barrier to large-scale direct air capture is the high current cost. If made less expensive, direct air capture technologies could be scaled up to remove very large amounts of carbon. Finally, carbon mineralization is currently constrained by many unknowns, including environmental impacts and likely cost. However, like direct air capture, carbon mineralization technologies could generate very large capacity if their costs and environmental impacts could be sufficiently reduced. These tables provide the evidence to support the committee's conclusions about the readiness of NETs:

Conclusion 2: Four negative emissions technologies (NETs) are ready for large-scale deployment: afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and bioenergy with carbon capture and sequestration (BECCS). The costs of these NETs can be low to medium (\$100/t CO_2 or less) and they have substantial potential to be safely scaled up from current deployment. These options also have co-benefits including:

- increased forest productivity (changes in forest management);
- improved agricultural productivity, soil nitrogen retention, and soil water holding capacity (enhanced uptake and storage by agricultural soils); and
- liquid fuel production and electricity generation (BECCS).

Conclusion 3: Current negative emissions technologies with direct costs that do not exceed \$100/t CO_2 can be safely scaled up to capture and store substantial amounts of carbon, but significantly less than ~1 Gt/y CO_2 in the United States and ~10 Gt/y CO_2 globally. Nonetheless, the global total of substantially below 10 Gt/y CO_2 is also substantially lower than the negative emissions that will likely be needed to adequately address the carbon and climate problem, according to virtually every recent assessment (EASAC, 2018; Fuss et al., 2018; Griscom et al., 2017; IPCC, 2014b; Mulligan, 2018; NRC, 2015b; UNEP, 2017). These "safe" upper bounds represent substantial fractions of the total emissions of ~ 6.5 Gt CO_2e in the United States and more than 50 Gt CO_2e globally, but would be challenging to achieve, because they would require unprecedented rates of adoption of agricultural soil conservation practices, forestry management practices, and waste biomass capture. Many programs intended to induce landowners to change forest, grazing, and cropland management in the past have achieved low levels of adoption. Research may help improve these outcomes, but this is uncertain. Also, approximately half the 1 Gt/y CO_2 in the United States and 10 Gt/y CO_2 globally would be achieved with BECCS fueled exclusively with biomass waste, and would require the collection and delivery of all economically

TABLE 8.1 Synthesis of Key NET Attributes with Current Technology and Understanding (Committee Assessment)

NET	Potential Rate of CO_2 Removal with Current Technology and Understanding (Gt/y CO_2)		Potential Capacity with Current Technology and Understanding (Gt CO_2)		Land Required (Mha)		Estimated Cost of Implementation at Scale ($/t CO_2)	Other Impacts
	United States	**Globally**	**United States**	**Globally**	**United States**	**Globally**		
Coastal Blue Carbon: Annual Carbon Burial	0.024-0.050[a]	0.13[b]-0.80[c]	0.26– 4.0[a]	8[b] -65[c]	0	0	10[d]	Multiple co-benefits; competition for land and submerged habitats
Terrestrial Carbon Removal and Sequestration: Afforestation/ Reforestation and Forest Management	0.25[e]-0.6[f]	2.5 [e]-9[f]	015-38[g]	1125-570[g]	(3-4)[e] - (16-20)[f]	(70-90)[e] - (350-500)[f]	15-50	Warms at high latitudes; reduces streamflow in areas with low rainfall
Terrestrial Carbon Removal and Sequestration: Agricultural Practices to Enhance Soil Carbon Storage	0.250[h]	3[h]	7[i]	90[i]	None	None	0-50	Improved soil health, H_2O retention, crop yields; sometimes may increase N_2O emission

Bioenergy with Carbon Capture and Sequestration (BECCS)	0.5[j]-1.5[k]	(3.5-5.2)[j] – (10-15)[k]	Limited by geologic storage capacity (electricity) or biomass availability (fuels)	Limited by geologic storage capacity (electricity) or biomass availability (fuels)	0[j]-78[k]	0[j]-(380-700)[k]	Electricity: 70 Fuels: 37-132	Biophysical impacts of feedstock production
Direct Air Capture: Solvent- and Sorbent-based Approaches	0[l]	0[l]	Limited by economic demand or by practical barriers to pace of scale-up	Limited by economic demand or by practical barriers to pace of scale-up	0.5-5.8[m] per Gt CO_2	0.5-5.8[m] per Gt CO_2	90-600[n]	Not assessed
Carbon Mineralization: Surficial Existing Tailings[o]	0.001	0.02-0.20	<1	10	NA	<1	10-20	Possible water and air contaminants
Carbon Mineralization: Surficial Mining and Grinding[o]	Unknown	Unknown	Essentially unlimited	Essentially unlimited	Tailings: 0.1-1 mm/Gt CO_2 /area of US	Tailings: 3-30 microns/Gt CO_2/area of oceans	50-500	Possible water and air contaminants

continued

TABLE 8.1 Continued

NET	Potential Rate of CO_2 Removal with Current Technology and Understanding (Gt/y CO_2)		Potential Capacity with Current Technology and Understanding (Gt CO_2)		Land Required (Mha)		Estimated Cost of Implementation at Scale (\$/t CO_2)	Other Impacts
	United States	**Globally**	**United States**	**Globally**	**United States**	**Globally**		
Carbon Mineralization: Produce Alkaline Water from Calcite[o]	NA	NA	NA	NA	NA	NA	<10	Possible concerns but no formal work published
Carbon Mineralization: *In Situ* Basalt and Peridotite[o]	Unknown	Unknown	Essentially unlimited	Essentially unlimited	NA	NA	20-5000	Possible concerns but no formal work published

NOTES: The factors that impact the ranges provided for each of the attributes vary among each of the NETs. In general, the upper bounds in the rate and capacity ranges for terrestrial-based NETs represent more aggressive programs and would likely lead to adverse societal, economic, and environmental impacts. The number of significant digits reflects state of knowledge among different NETs and between U.S. and global estimates.

[a] Low and high removal rate based on approximately 25 percent and 100 percent implementation for restoration and nature-based adaptation, respectively, active management of existing areas and managed wetland transgression.

[b] Global removal rate based on coastal wetland area lost since approximately 1980 (Pendleton et al. 2012) and annual burial rate with restoration; does not include active management of existing areas or managed wetland transgression.

[c] Based on recovering emissions from coastal wetland area lost since approximately 1980 minus estimated storage (stocking wetlands from carbon sourced from outside of coastal areas).

[d] Assumes that carbon removal and storage objectives are added to projects undertaken for other purposes. Cost is all monitoring and verification.

[e] Lower number has minimal impact on food and biodiversity. See Box 3.1 for rate and capacity estimates with frontier technologies.

[f] Larger number has large impacts on food and biodiversity.

[g] Capacity estimates assume carbon stock increases over a duration of 80 years until the end of the century for afforestation/reforestation, and 30 years for forest management, at which time net increases in biomass stocks cease to be greater than a business as usual baseline.

[h] CO_2 removal rate and capacity that are feasible, with current technologies, without compromising food supply or biodiversity from large-scale land conversions. See Box 3.1 for rate and capacity estimates with frontier technologies.

[i] Capacity estimates assume that carbon gains occur over 30 year time period, after which time soil carbon stocks approach a new equilibrium with no further carbon stock increases.

[j] Assumes only waste biomass used as a feedstock.

[k] Assumes feedstocks include waste biomass and dedicated energy crops.

[l] Future economic demand for $100/t CO_2 direct air capture could be in the tens of gigatons per year.

[m] Depends on the size of the contactor, the spacing requirements of multiple contactors, and contactor configuration.

[n] Upper bound is the current demonstrated cost of direct air capture (see Chapter 5).

[o] There is a wide variety of carbon mineralization applications and a limited number of published analyses and demonstrations. See Tables 6.1 and 6.2 for additional detail.

TABLE 8.2 Synthesis of Key Attributes for CO_2 Sequestration Only with Current Technology and Understanding (Committee Assessment)

NET	**Potential Rate of CO_2 Removal with Current Technology and Understanding ($Gt/y\ CO_2$)**	**Potential Capacity with Current Technology and Understanding ($Gt\ CO_2$)**		**Estimated Cost of Implementation at Scale ($\$/t\ CO_2$)**	**Other Impacts**
		United States	**Global**		
Coastal Sequestration (Augmentation with Carbon from Other Areas)	0.008-0.034[a] (annual sequestration from augmentation techniques based on area of projects completed per year for other purposes)	0.15–1.43[a]	12–18[b]	NA	Not assessed
Ex Situ Sequestration in Existing Brucite, Olivine and Serpentine[c]	0.012-0.04	~ 0	0.6–2.0	10 [brucite] 100 [olivine] 200-500 [serpentine]	Permanence higher, risk of groundwater contamination similar, leak risk lower, compared to saline aquifer storage. Remediates asbestos risk.
In Situ Sequestration in Peridotite and Basalt[c]	Up to 32	~100,000	~1,000,000	10-30	Permanence higher, risk of ground water contamination and induced earthquakes similar, leak risk lower, compared to saline aquifer storage.

Sequestration after Reactions With Municipal and Industrial Waste for Environmental Cleanup[c]	0.05–1.6	Not assessed	0.5–5.0	75->1,000	Remediates risk of water contamination.
Geologic Sequestration: Saline Aquifer Storage	1 Gt/y CO_2 in the US would require an increase of 10% per year given the current base of 65 Mt/y CO_2[d]	2600-26,000 with a median of 3000[e]	5,000–25,000[f]	7–13[g]	Permanence very high (>99%). Surface leaks likely to be acute rather than chronic and so can be remediated. Induced earthquakes if injection pressures too high. Some risk of groundwater contamination.

[a] Based on approximately 25 percent and 100 percent implementation of areas augmented with carbon sourced from outside coastal areas

[b] Based on estimated fraction of areas augmented with carbon in the United States.

[c] There is a wide variety of carbon mineralization applications and a limited number of published analyses and demonstrations. See Tables 6.1 and 6.2 for additional detail.

[d] Practical limits will be set by the availability of CO_2, pipelines, regulatory infrastructure, and public opinion

[e] DOE, 2015b; U.S. Geological Survey, 2013.

[f] Benson et al., 2012; Benson et al., 2005.

[g] The wide range reflects the highly site-specific nature of geologic sequestration projects. Primary variables include the depth of the formation, number of injection wells required, existing land uses, and ease of deploying monitoring programs.

available agricultural, forestry and municipal waste to a BECCS facility able to use that type of waste. This would be logistically challenging anywhere, and especially in countries with limited organizational capacity. It is thus important to understand that "substantially less than 1 Gt/y CO_2 in the United States and 10Gt/y CO_2 globally" means that achievable limits could be smaller by a factor of two or more.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2014b) analyzed some paths that would limit global warming over preindustrial levels to less than 2.0°C, and Fuss et al. (2018) recently published a comprehensive review of scenarios that limit warming to 1.5°C and to less than 2.0°C. The breadth of the scenarios considered complicates the analysis, but, in aggregate, the message is clear and not very different for either target. Net anthropogenic emissions of all greenhouse gases must decline from more than 50 Gt CO_2e today to approximately less than 20 Gt CO_2e at midcentury and to approximately zero by 2100 (Figure 8.1). Approximately 10-20 Gt CO_2e of gross anthropogenic emissions come from sources that would be very difficult or expensive to eliminate, including a large fraction of agricultural methane and nitrous oxide. Feasible scenarios, such as the one in Figure 8.1, thus rely on 10 Gt CO_2 of removal and storage approximately by midcentury and 20 Gt CO_2 by the century's end.

Conclusion 4: If the goals for climate and economic growth are to be achieved, negative emissions technologies will likely need to play a large role in mitigating climate change by removing ~10 Gt/y CO_2 globally by midcentury and ~20 Gt/y CO_2 globally by the century's end.

At substantially less than 10 Gt/y CO_2, the available safe and economical NETs are insufficient to limit warming to 2°C or less and are by no means guaranteed to achieve that level of abatement. Having more options is likely to reduce overall risk and costs and to increase the chances of success. Thus, existing options would need to improve, and new options would need to be developed—or both. This report proposes a research program that would reduce the costs of all NETs and expand the portfolio of safe and economical options. The case for new research on NETs does not rest solely on the adoption of a 2°C climate target. NETs would reduce the cost and the disruption of any program to limit climate change by reducing the need to eliminate emissions from the most recalcitrant or expensive sources of CO_2, such as those from agriculture, land-use change, or aviation fuels. At less than \$20/t CO_2, some currently available NETs are less expensive than most mitigation methods (Table 8.1). For this reason, Nationally Determined Contributions submitted under the Paris agreement already include approximately 1 Gt/y CO_2 of negative afforestation/reforestation emissions.

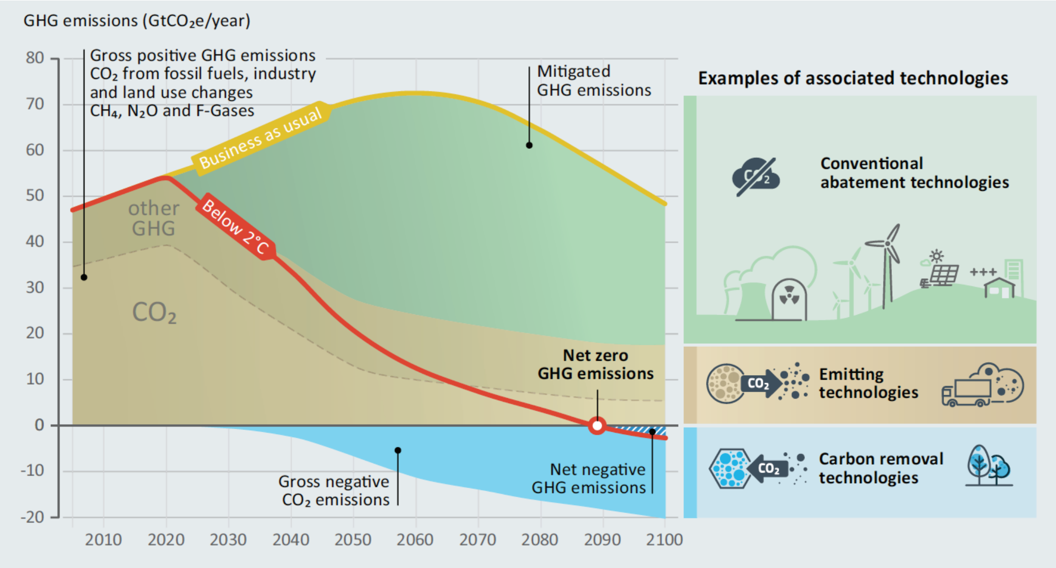

FIGURE 8.1 Scenario of the role of negative emissions technologies in reaching net zero emissions (UNEP, 2017).
NOTES: Green represents mitigation, brown represents anthropogenic greenhouse gas emissions, and blue represents anthropogenic negative emissions. Negative emissions of 10 Gt CO_2 are required by the late 2050s and of 20 Gt CO_2 by the late 2090s because of ongoing positive emissions from essential activities such as agriculture (mostly N_2O and CH_4) and activities that are very expensive to mitigate.

The committee recognizes that the federal government has many other research priorities, including others in mitigation and adaptation to climate change. Multiple reasons exist to pursue research on NETs. First, states, local governments, corporations, and countries around the world are making substantial investments to reduce their net carbon emissions and plan to increase these investments. Some of these efforts already include negative emissions. This means that advances in NETs will benefit the U.S. economy if the intellectual property is held by U.S. companies. These advances would increase U.S. competitiveness, create new jobs, enhance exports, and potentially benefit agricultural and silvicultural yields and the stability of farm and forestry economies.

Second, as damages mount, the United States will inevitably increase efforts to limit climate change in the future. Third, the United States is already making a substantial effort, including the new 45Q tax credit rule[5] that provides \$50/t CO_2 for carbon

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[5] See https://www.law.cornell.edu/uscode/text/26/45Q (accessed January 29, 2019).

capture and storage, including direct air capture as a source, which would leverage the value of new investments in NET research.

Table 8.1 highlights the primary limiting factors for each of the NETs. For example, afforestation/reforestation and BECCS are primarily limited by competing needs for the land, removal and storage in agricultural soils by the low per-hectare rate of CO_2 removal, direct air capture by its current high cost, and carbon mineralization and coastal/near-shore blue carbon approaches by a lack of fundamental understanding of future uptake rates. These constraints are also reflected in Table 8.1 by the large ranges for potential CO_2 removal rates, capacities, and land requirements for forestry approaches and BECCS; by the large current costs for direct air capture; and by the large ranges in cost for the two high-capacity carbon mineralization options (ex situ mining and grinding of reactive rocks and in situ capture and sequestration in basalt or peridotite). If we could find a way to extend afforestation/reforestation and BECCS to hundreds of millions of hectares of arable land, without disrupting the food supply or causing the clearance of remaining tropical forests, then these options could supply more than 10 Gt/y CO_2 of negative emissions globally, as shown by integrated assessment model (IAM) results reviewed in IPCC (2014b) (Table 8.1). Similarly, simply disposing of wood products in landfills designed to prevent decomposition could double the global capacity of forest management approaches. Inexpensive direct air capture or carbon mineralization would be revolutionary, because the potential capacity of each of these options is larger than the need (Table 8.1).

FACTORS AFFECTING SCALE UP

The committee considered a range of factors that affect the scale-up of NETs. These include the availability of land given the competing needs for food and biodiversity preservation, other environmental constraints, energy requirements, high cost, practical barriers, permanence, monitoring and verification, governance, and insufficient scientific or technological understanding. These factors helped inform the recommended research program for each NET and are summarized here.

The Land Constraint

The land constraint is pivotal to the conclusion that fundamentally new CO_2 removal options are needed. All recently published assessments of NETs highlight the dangers of competition for land among afforestation/reforestation, BECCS, food production, and biodiversity preservation, but also report large upper bounds for negative emissions from BECCS and from afforestation/reforestation, which would require hundreds of millions of hectares of land (i.e., EASAC, 2018; Fuss et al., 2018; Griscom et al., 2017; IPCC, 2014b; Mulligan et al., 2018; UNEP, 2017). Until research proves otherwise, it is prudent to view as impractical upper bounds for afforestation/reforestation and BECCS deployment of more than 10 Gt/y CO_2.

The committee believes it is best to assume that every square meter of productive land on Earth is already used for some purpose (Smith et al., 2010). That is, every parcel not covered by ice or desert is already devoted to producing crops or meat, preserving remaining biodiversity, providing valued ecosystem services, producing wood fiber, or providing urban and suburban space for people (according to FAO [2008], Earth currently has approximately 3.7 billion hectares of forest, 1.6 billion hectares of cropland, 3.5 billion hectares of pasture, and a trace that is urban or suburban). Although substantial amounts of land classified as "degraded" or "marginal" exist in national and international inventories, one person's nonessential land is typically another person's source of essential livelihood, refuge, or preserve. As mentioned in Chapter 3, one recent study's estimate of 1,300 Mha[6] of marginal land includes land that supports one-third of humanity with subsistence-level food and fuel (Kang et al., 2013).[7]

To complicate matters, two additional land-use problems of daunting global magnitude should be managed at the same time as climate change. Food demand is projected to double by midcentury because of increased meat consumption with increased wealth and population growth (Foley et al., 2011). Extinction rates are estimated to be 100-1,000 times the background rate from the fossil record, and 80 percent of threatened species are at risk because of habitat loss, with 90 percent of these threatened because of agricultural expansion (MEA, 2005b; Thornton, 2010; Tilman et al., 2011). The combination of climate change with food demand and continued habitat loss could cause a mass extinction (Barnosky et al., 2011; Tilman et al., 1994). Competition among land uses will only strengthen through the current century as the demand for food and fiber grows, and as ecosystems and agriculture contend with worsening climate change. Fortunately, most proposed solutions for the food problem suggest the possibility to meet midcentury food demand on roughly the current agricultural land (crop plus pasture) by increasing agricultural productivity and reducing food waste (Foley et al., 2011; Thornton, 2010; Tilman et al., 2011). Some studies also propose that diets need to become modestly less meat-rich (Foley et al., 2011), but the link between meat consumption and income has proven resistant to change.

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[6] Mega hectare (ha x 10^6).

[7] Estimates of marginal land are uncertain due to inconsistencies in the definition. See Chapter 3 for a detailed discussion.

The inescapable conclusion is that repurposing a substantial amount of current agricultural land to produce feedstocks for BECCS or for afforestation/reforestation, could significantly impact food availability and food prices (as predicted by IAMs in IPCC, 2014b). In addition to harming the world's poor, food price shocks have substantial national security implications (see Bellemare, 2015; Carleton and Hsiang, 2016; Hsiang et al., 2013; Werrell and Femia, 2013). Because remaining biodiversity is already threatened by habitat loss exacerbated by climate change (Barnosky et al., 2011), devoting a substantial amount of nonagricultural land to land-hungry NETs would likely cause a substantial increase in extinction (Smith et al., 2008). Moreover, land taken for afforestation/reforestation or BECCS from either agriculture or production forestry would create economic pressure to convert remaining primary forest to cropland and pasture to meet continued food demand, or to harvest it to meet continued fiber demand. Similarly, a forest management approach to increase the length of time between successive forest harvests would increase the average biomass of carbon on fiber-producing lands, and also, at least temporarily, would increase economic pressure for increased harvest in other locations. The consequences would be additional biodiversity loss and additional CO_2 emissions from deforestation (Fargione et al., 2008). This problem is unavoidable if a substantial amount of land is converted from one use to another.

Although some IAMs and other models attempt to estimate costs of far-field effects associated with land-use change, including those described above, these estimates are highly uncertain (IPCC, 2014b; Popp et al., 2014; Riahi et al., 2017; Rose et al., 2014), and existing models may omit what could be the most important costs. For example, the security implications of land-use change that affects food production are not explicitly included in IAMs. In their recent assessment of land-use options for carbon mitigation, Griscom et al., 2017 attempted to minimize adverse consequences of land use transfers by excluding or limiting the most problematic, but it is not clear how well such restrictions could be maintained in the face of deliberate economic incentives for afforestation/reforestation and BECCS. Because this problem combines limited understanding with the most severe consequences if we get it wrong, the committee believes that humanity should develop new high-capacity NETs such as low-cost direct air capture and carbon mineralization. The safe levels of afforestation/reforestation, forest management approaches, and BECCS in Table 8.1 are set to minimize the risk of unintended consequences of land-use transitions.

Other Environmental Constraints

Other environmental constraints vary idiosyncratically among the various NETs. Because forests established at high latitudes decrease albedo by, for example, reducing the reflectivity of snow cover, afforestation/reforestation at high latitudes would likely cause net warming despite the cooling caused by the forest's CO_2 uptake. In addition, forests established in regions with limited rainfall have adverse effects on streamflow, irrigation, and groundwater supplies (see Chapter 3). *Ex situ* methods of carbon mineralization would create enormous volumes of waste rock that may contaminate water and/or air. Agricultural soils options generally have large positive side benefits, including increased productivity, water holding capacity, stability of yields, and nitrogen use efficiency, but sometimes cause increased N_2O emissions. Afforestation/reforestation, BECCS, and potentially some direct air capture routes may have substantial water requirements. In particular, irrigated bioenergy crops may lead to a trade-off between land and water requirements, in addition to freshwater ecosystem degradation and biodiversity loss.

Energy Requirement

Direct air capture and some carbon mineralization options require a large energy input per ton of CO_2 captured, which increases costs. Solvent-based direct air capture systems require roughly 10 GJ to capture a ton of atmospheric CO_2 and sorbent-based systems require roughly 5 GJ. To put this into perspective, combustion of 100 gallons of gasoline releases about 13GJ of energy and emits about a ton of CO_2. Gt-scale direct air capture thus necessitates an enormous increase in low- or zero-carbon energy to meet these energy demands, which would compete with use of such energy sources to mitigate emissions from other sectors. Table 8.1 includes the large land areas required to produce this energy from renewable sources, not including nuclear or natural gas with CCS options.

High Cost

The primary impediment to direct air capture is high cost. Climeworks, which has the only existing commercial direct air capture machine, captures CO_2 at a reported cost of \$600/t CO_2 (Daniel Egger, personal communication, October 11, 2018). A recent paper by Keith et al., 2018 estimates costs between \$200 and \$300/t CO_2 for CO_2 captured from the atmosphere by a solvent-based system (although costs are lower if the CO_2 captured from natural gas combustion used to produce heat in the system are included). The analysis in Chapter 5 suggests that the cost of sorbent-based direct air capture and sequestration might be reduced to approximately \$90/t CO_2. The chapter further states that it is too early to determine whether sorbent- or solvent-based systems will ultimately prove to be the least expensive.

The estimated cost of capture and sequestration for BECCS systems that produce electricity is \$70/t CO_2 (Table 8.2), largely because of the low thermal efficiency relative to fossil electricity. The costs for BECCS systems producing liquid fuels and char might be lower (Table 8.2) but depend on the uncertain economics of char. In addition, negative emissions from the liquid fuels/biochar pathway are smaller, per unit of biomass, than from the biomass electricity/carbon-capture pathway.

The costs of carbon mineralization are difficult to determine because fundamental understanding of the processes is lacking. The costs of the two high-capacity options (ex situ mining and grinding of reactive rocks and in situ capture and sequestration in basalt or peridotite) may be as low as \$20-\$50/t CO_2 or could be prohibitively expensive. Costs of terrestrial carbon removal and sequestration approaches are comparatively well understood and are relatively low.

Practical Barriers

Practical barriers to scaling up deployment of NETs include shortages of materials, financing and human capital, robust and reliable financial incentives, as well as social acceptance of large-scale deployment. For example, a 10 percent per year increase from the 65 Mt/y CO_2 that is currently injected underground for CO_2-enhanced oil recovery and saline aquifer sequestration is needed in order to scale up underground injection for geological sequestration. If there is a serious attempt to limit warming to 2°C, then comparable or greater rates of growth will be required of every available NET. At these rates, scale-up could become limited by materials shortages, regulatory barriers, infrastructure development (i.e., CO_2 pipelines and renewable electricity), the availability of trained workers, and many other barriers. However, afforestation/reforestation, forest management, and agricultural soils activities in the United States are already supported by well-developed state and federal (U.S. Department of Agriculture [USDA]) extension services with decades of experience in facilitating changes in land-use practice, augmentable thorough additional technology transfer, training, and outreach.

Furthermore, humans often resist actions that appear to be in their economic interest. For example, historical adoption rates of agricultural soil conservation and forestry management practices that would save farmers and forest landowners money have been surprisingly low, as have dietary changes, such as reduced meat consumption, that would increase health while freeing agricultural land for forestry NETs and BECCS. These behaviors could limit deployment of NETs, as could public resistance to new local infrastructure, but they are not well represented in IAMs. Although a general treatment is beyond the scope of its tasks, the committee did consider social science issues. In particular, the committee supports the need to better understand landowner responses to incentives for forestry, agricultural soils, and coastal NETs, as well as general improvement in the ability of IAMs to predict responses to incentives (see, e.g., items 6, 8, 12, and 16 in Table 8.3).

Permanence

Carbon stock increases through terrestrial (afforestation/reforestation, forest management, and agricultural soils) and coastal blue carbon options are all reversible if the carbon sequestering practices are not maintained. Forested land can be cleared again for agriculture, liquidating the biomass carbon. Reverting to intensive tillage would reverse much or all of the soil carbon gains from reduced tillage practices in agricultural soils methods (Conant et al., 2007; Grandy and Robertson, 2007; Minasny et al., 2017). A restored coastal wetland could be drained again for development. Nonetheless, appropriate policies and governance could reduce the frequency of any such reversals, and the reversals are themselves reversible. Moreover, NETs plus reversals for forest plantings (afforestation/reforestation) will eventually result in an age-structured mosaic of patches, where age measures the time since the most recent establishment of negative emissions practices in a patch. The total carbon stored by the mosaic of patches will increase with mean age, despite the presence of reversals. In contrast, carbon lost from coastal wetlands because of too-rapid sea level rise cannot be recovered in the same site. Likewise, carbon lost from forest or soil carbon because of permanent changes in climate that decrease the equilibrium carbon content of ecosystems cannot be recovered at the same sites. Biochar soil amendment has been proposed as a promising path for long-term carbon removal strategy (for both agricultural soils and the biomass-to-fuel and biochar BECCS pathway); however, questions remain about the long-term stability of biochar in soil environments.

The other BECCS pathways and direct air capture have comparatively minor issues of permanence. CO_2 can leak from saline aquifers, but at rates low enough to remediate. Permanence would be very high in mineralization of basalt or peridotite. Of note, the high-capacity backstop of CO_2 removal and sequestration that would be provided by reliable low-cost direct air capture and mineralization would reduce concerns of permanence compared to not only other sequestration technologies, but also solar radiation management, which presents major concerns regarding its permanence (Jones et al., 2013a; NRC, 2015a). As discussed in Chapter 1, the scientific and economic issues associated with the length of time that CO_2 remains in sequestration, and the value of that time, are daunting.

TABLE 8.3 Research Plan and Budget for Negative Emissions Technologies (abbreviated from research tables in Chapters 2-7).

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
1	Coastal	Basic research in understanding and using coastal ecosystems as a NET	6	5-10	5 projects at $2M/y for 10 years to address fate of organic carbon produced and buried in soils/sediments of coastal ecosystems; 5 projects at $2M/y for 10 years to address change in area coastal blue carbon ecosystems in response to change in major climate change or sea level rise and management drivers; 5 projects at $2M/y for 5 years to address selection of materials and coastal plants/phenotypes producing high organic carbon density materials with slow decay rates buried in coastal sediments carbon.	NSF USACE DOE Industry	Scientific/ Technical Understanding Permanence
2	Coastal	Mapping current and future (i.e., after sea level rise) coastal wetlands.	2	20	$2M/y (tidal wetland: $1.5M; seagrass: $500K) for 20 years.	NASA DOE NOAA USFS EPA	Scientific/ Technical Understanding Permanence Monitoring and Verification

3	Coastal	Integrated network of coastal sites for scientific and experimental work on carbon removal and storage.	40	20	15 engineered sites at a cost of $1M/y per site (approx. LTER); 20 augmented managed and engineered sites at a cost of $500K/y; 8 new managed sites at $500K/y (i.e., wetland transgression – 0-2 ft and seagrass); 5 U.S.-scale synthesis activities (wetland: 3; seagrass: 2) at a cost of $200K/y per activity.	NSF NOAA	Scientific/ Technical Understanding Cost Other Environmental Constraints
4	Coastal	National Coastal Wetland Data Center, including data on all restoration and carbon removal projects.	2	20	The center would make the mapping data (above) public and would overlay information about all coastal restoration and engineering projects, including carbon removal and storage projects. One center at $2M/y.	NOAA USACE	Scientific/ Technical Understanding Monitoring and Verification Governance

continued

TABLE 8.3 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
5	Coastal	Carbon-rich NET demonstration projects & field experiment network	10	20	Carbon-rich NET demonstration projects and field experiment network (15 sites funded at $670K/site/y).	NSF NOAA USACE DOE Industry	Scientific/Technical Understanding Cost Monitoring and Verification Permanence Other Environmental Constraints
6	Coastal	Coastal blue carbon project deployment.	5	10	Social science research on cost effective adaptive management of coastal blue carbon, and on the response of coastal land owners and managers to carbon removal and storage incentives. $5M/y.	NSF NOAA	Practical Barriers Governance
7	Afforestation/Reforestation, Forest Management	Monitoring of forest stock enhancement projects	5	≥3	Develop ($1M) and operate ($4M/y) a national monitoring system for forest carbon that would complement the USFS forest inventory (currently funded at $70 M/y). This would monitor afforestation/reforestation and forest management	USFS and partners	Monitoring and Verification Governance

					activities remotely and measure carbon in a statistical sample of locations. A system capable of measuring international far-field effects (i.e. enhanced harvest elsewhere in response to reduced harvest in U.S.) would cost 10 to 20 times more.		
8	Afforestation/ Reforestation, Forest Management, BECCS	IAM and regional life cycle assessment of BECCS mitigation potential and secondary impacts	3.7-14	10	Economic and behavioral studies and modeling to estimate how much land use change will occur elsewhere in the world in response to diversion of land to afforestation/reforestation or BECCS dedicated energy crops, or in response to reduced wood harvest (forest management). Attempt to improve understanding of impacts of land diversion to afforestation/reforestation and energy crops on food prices, food security, ecosystem services, biodiversity, albedo, and hydrology. Increase spatial resolution of models.	DOE NSF USDA EPA Universities and national labs	Land Other Environmental Constraints Monitoring and Verification Permanence Governance

continued

TABLE 8.3 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
9	Afforestation/ Reforestation, Forest Management	Forest demonstration projects: increasing collection, disposal, and preservation of harvested wood; and forest restoration	4.5	3	Demonstration projects to improve collection and disposal of wood products after use (3 3-year projects at 500K/y each); 3 multiyear projects for preserving harvested wood in different environments (500K/y each); and 3 multiyear projects to demonstrate carbon benefits of forest restoration in different geographic regions ($500K/y each).	USDA and NSF USFS and partners	Practical Barriers Other Environmental Constraints Governance
10	Forest Management	Preservation of harvested wood	2.4	3	Landfill designs for achieving the lowest possible rate of wood decomposition (3 multiyear projects, each $800K). IAM and LCA (see item 8).	EPA USFS	Frontier
11	Forest Management	Research on greenhouse gases and social impacts of reducing traditional uses of biomass for fuel	1	3	Research on greenhouse gases and social impacts of reducing traditional uses of biomass for fuel, which involves households and small entities using wood biomass for heating and cooking. Funding for initiation of 1 multiyear project.	USDA NSF	Other Environmental Constraints Energy Use Governance

12	Forest Management	Social sciences research on improving landowner responses to incentives and equity among landowner classes	1	3	Extension and outreach educational programs for transferring research findings and technologies to farmers and practitioners. Funding for initiation of 3 multiyear projects.	USDA NSF	Practical Barriers Governance
13	Agricultural Soils	National agricultural soils monitoring system	5	Ongoing	Augmentation of USDA's existing NRI system. Full buildout to approximately 5,000-7,000 NRI locations with soil sampling and analysis carried out at intervals of 5-7 years (on an annual rotating basis similar to the USFS FIA system). Monitor adoption and permanence of agricultural soils on U.S. agricultural lands.	USDA	Monitoring and Verification Permanence Governance
14	Agricultural Soils	Experimental network improving agricultural soil carbon processes.	6-9	≥12	Field experiments to rigorously evaluate and further develop region-specific best management practices for soil carbon sequestration (and net greenhouse gas reductions). 10-15 sites at $600K/site.	USDA Land grant universities	Scientific/Technical Understanding Other Environmental Constraints Cost Governance

continued

TABLE 8.3 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
15	Agricultural Soils	Data-model platform for predicting and quantifying agricultural soil carbon removal and storage	5	5	Develop improved tool for predicting and quantifying soil carbon storage accurately and cost effectively. Initial development should focus on systems integration, including of existing data sources and models.	USDA NSF	Science/Technical Understanding Monitoring and Verification Other Environmental Constraints Cost Governance
16	Agricultural Soils	Scaling up of agricultural soils sequestration activities	2	3	Support for initiation of 4-5 regional projects per year to identify solutions to overcome barriers to adoption. Ideally coupled to programs in Items 14-15. 4 projects at $500K/y.	USDA NSF	Practical Barriers Governance
17	Agricultural Soils	High carbon input crop phenotypes	40-50	20	Screen and develop crop varieties and species specifically to enhance storage in agricultural soils. The DOE/ARPA-E ROOTS program is currently funded for $35M total.	DOE USDA NSF	Frontier

18	Agricultural Soils	Soil carbon dynamics at depth	3-4	5	Develop and test methods of deep inversion of soils, which may increase sequestration by ~1 tCO_2/y for decades. 4-6 projects per year at $750K/project.	USDA NSF	Frontier
19	Agricultural Soils, BECCS	Biochar studies	3	5-10	Assess biochar's effects on agricultural productivity, soil carbon, nutrient use, water use, and albedo. Assess longevity of biochar in soils. Determine the carbon storage limits that can be achieved with biochar. 3-5 projects per year.	DOE USDA NSF	Scientific/ Technical Understanding
20	Agricultural Soils, Carbon Mineralization	Reactive mineral additions to soils	3	10	Assess weathering rates of reactive minerals (i.e. olivine) added to agricultural soils and effects on agricultural productivity, soil carbon, nutrient use, water use, and albedo. Determine the carbon storage limits that can be achieved with mineral addition.	DOE USDA NSF	Frontier
21	BECCS	Biomass-to-fuel with biochar	40-103	10	Assess the carbon removal potential of all biomass conversion to fuel pathways and develop negative carbon fuel pathways that are cost-competitive.	DOE USDA Industry	Scientific/ Technical Understanding Cost

continued

TABLE 8.3 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
22	Direct Air Capture	Basic research and early phase technology development	20-30	10	Research on low-cost sorbents, ways to reduce large thermal energy requirements, new materials with better sorption capacity and reaction and diffusion kinetics, advances in solvent and sorbent contactor design, identify any environmental contaminants released, increase gas throughput and reduce pressure drop. ~30 projects per year at $1M/project, each ~3 years in length.	DOE	Scientific/ Technical Understanding Cost Energy Use Other Environmental Constraints
23	Direct Air Capture	Independent techno-economic analysis, third-party materials testing and evaluation, and public materials database	3-5	10	Independent techno-economic analysis of products of basic research (Item 22) and a public database to facilitate rapid progress.	Industry	Scientific/ Technical Understanding Cost Energy Use
24	Direct Air Capture	Scaling up and testing of air capture materials and components	10-15	10	Scale materials synthesis to >100 kg, design novel system components and equipment for a pilot-scale effort, test integrated lab-scale air capture system (>100 kg/d CO_2).	DOE	Scientific/ Technical Understanding Cost Energy Use

25	Direct Air Capture	Third-party professional engineering design firm assistance for the above effort, including independent testing, and a public database	3-10	10	Professional help with a project's engineering design, including mass and energy balances, process flowsheets, preliminary piping and instrument diagrams, main equipment definitions and sizing, preliminary bill of materials, risk assessment, and process economics analysis. Independent testing of materials and components on standardized hardware at national test center (Item 27). Maintenance of a public database of tested materials and their performance.	DOE Industry	Scientific/ Technical Understanding Cost Energy Use
26	Direct Air Capture	Design, build, and test pilot air capture system (>1,000 tCO_2/y)	20-40	10	\$20M/project, each with 3 years duration, and 1-2 projects/year.	DOE	Scientific/ Technical Understanding Cost Energy Use
27	Direct Air Capture	National Air Capture Test Center support of pilots	10-20	10	Establish National Air Capture Test Center to support pilot efforts, including 3rd-party front-end engineering design and economic analysis, and creation and maintenance of a public database on plant performance.	DOE NIST Industry	Scientific/ Technical Understanding Cost Energy Use

continued

TABLE 8.3 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
28	Direct Air Capture	Design, build, and test air capture demonstration system of >10,000 t CO_2/y	100	10	$100M/project, 1 project/year each with 3-5 years duration	DOE	Scientific/ Technical Understanding Cost Energy Use
29	Direct Air Capture	National air capture test center support of demonstrations	15-20	10	Engage national test center to support demonstration projects and maintain public record of full-scale plant performance and economics.	DOE NIST Industry	Scientific/ Technical Understanding Cost Energy Use
30	Carbon Mineralization	Basic research on mineralization kinetics	5.5	10	5 projects at $500K-$1.5M for 10 years.	USGS DOE NSF	Scientific/ Technical Understanding
31	Carbon Mineralization	Basic research on rock mechanics, numerical modeling, and field studies	17	10	Exploration of positive and negative feedbacks between reaction and fluid flow, for in situ carbon mineralization, in situ mining, geothermal power generation, extraction of oil and gas from tight reservoirs, ensuring integrity of reservoir	USGS DOE NSF	Frontier

					caprock and wellbore cement. \$6M/y for rock mechanics, \$5M/y numerical modeling, and \$5M/y for field studies. 22 projects at \$0.5-\$1.5M for 10 years.		
32	Carbon Mineralization	Mapping of reactive mineral deposits and existing tailings (scoping for pilot studies)	7.5	5	Minerals and rocks include all that react rapidly and exothermically with CO_2, including brucite, olivine, peridotite, basalt etc. 5 projects at \$1.5M for 5 years.	USGS DOE NSF	Science/Technical Understanding Other Environmental Constraints Governance
33	Carbon Mineralization	Surficial (ex situ) carbon removal pilot studies	3.5	10	Ex situ mine tailings, broadcast of reactive minerals and rocks on soils, beaches, shallow ocean. 5 projects at \$0.25- \$1.0M for 10 years.	USGS DOE NSF	Cost Energy Use Other Environmental Constraints Governance Monitoring and Verification Practical Barriers

continued

TABLE 8.3 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
34	Carbon Mineralization	Medium-scale in situ field experiment in peridotite rock	10	10	No prior experiments on field scale, initial low porosity requires stimulation and/or practical knowledge of positive feedbacks such as "reaction-driven cracking," $10M/y for 10 years, constant annual cost for phased project with increasing annual expenses for successive phases.	USGS DOE NSF	Frontier
35	Carbon Mineralization	Development of a resource database for carbon mineralization	2	5	Database that would allow the results of carbon mineralization research activities are disseminated broadly to the research community. 4 projects at $500K for 5 years.	USGS	Scientific and Technical Understanding Practical barriers to scale up
36	Carbon mineralization	Study of the environmental impact of mineral addition to terrestrial, coastal, and marine environments	10	10	12 projects at ~ $800K/y.	NSF USGS DOE	Scientific and Technical Understanding Costs Other Environmental Constraints Governance Practical barriers to scale up

37	Carbon Mineralization	Examination of the social and environmental impact of an expanded extraction industry for the purpose of CO_2 removal	5	10	10 projects at $500k for 10 years.	NSF	Cost Other Environmental Constraints Practical barriers to scale up

NOTE: ARPA-E=Advanced Research Projects Agency-Energy, CCUS=Carbon Capture, Utilization and Storage, DOE=Department of Energy, EPA=Environmental Protection Agency, FIA=Forest Inventory and Analysis, FTE=Full-Time Equivalent, IAM=Integrated Assessment Model, LCA=Life Cycle Assessment, LTER=Long-Term Ecological Research, NET=Negative Emissions Technology, NIST=National Institute of Standards and Technology, NRI=National Resource Inventory, NSF=National Science Foundation, ROOTS=Rhizosphere Observations Optimizing Terrestrial Sequestration, USACE=US Army Corps of Engineers, USDA=US Department of Agriculture, USFS=US Forest Service, USGS=US Geological Survey.

Monitoring and Verification

Monitoring and verification will be critical components of any large-scale deployment of NETs. It is important to distinguish between the monitoring and verification required in a private transaction to determine whether a single project has delivered the promised negative emissions, and that required by a nation to determine, for example, the effectiveness of its overall mitigation efforts. The former requires direct measurement of the carbon stored on site, while the latter could rely on low-cost monitoring of an activity, such as reforestation or improved crop rotations, together with more limited higher-cost direct measurements of a statistical sample. Of course, direct measurements everywhere would be preferable but may not always be worth the added expense.

Afforestation/reforestation, forest management, and agricultural soils are sufficiently well understood that, in most cases, they could be deployed in the United States with remote monitoring and verification backed up by onsite measurements in a statistical sample. Effective monitoring and verification here will not require additional fundamental research into carbon dynamics. Rather it will require improved systems to monitor forest carbon and soil carbon on agricultural lands, expanded remote sensing of land use and management practices, better integration of existing data sets and models, and selected improvements in global monitoring to help address leakage (i.e., land-use changes in one location inducing land-use changes in other locations). This also applies to BECCS, with the proviso that emissions from transport and processing of biomass should also be verified. BECCS-to-fuels with biochar has the separate complication that emissions from char decomposition are not fully understood. Again, implementation of afforestation/reforestation, forest management, and BECCS above the levels in the second and third columns in Table 8.1 would probably cause far-field changes, such as increased deforestation elsewhere, and thus require global monitoring and verification. See the National Academies report *Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements* (NRC, 2010) for a full treatment of this issue.

Coastal blue carbon and storage could be monitored and verified with inexpensive remote methods backed up by onsite measurements of a statistical sample. However, fine-scale spatial heterogeneity in coastal wetlands will likely require finer spatial resolution than monitoring and verification of afforestation/reforestation, forest management, agricultural soils, and BECCS. Because of landscape and shoreline evolution, intensive coastal verification might have to continue indefinitely.

Some forms of in situ and ex situ mineralization that store CO_2 in inert and essentially permanent solid form might have lower monitoring and verification costs than any of the other NETs. However, dispersal of reactive rock material in soil, along beaches, or into the shallow ocean could be as difficult, or more difficult, to verify than agricultural soils. Monitoring and verification of direct air capture would be straightforward. Monitoring and verification of sequestration in saline aquifers requires sophisticated methods such as seismic imaging, measuring pressure in and above the sequestration reservoir, and routine measurements of well integrity.

Governance

Appropriate governance of NETs is obviously critical because overly lax oversight would lead to ineffective CO_2 removal and loss of public confidence, while overly strict oversight would limit deployment. Governance is especially critical when large-scale deployment is imminent. Currently, governance is well established only in those sectors covered by a national or international agreement, including afforestation/reforestation (under the United Nations Framework Convention on Climate Change) and saline aquifer storage (under the Underground Injection Protocol of the Safe Water Drinking Act). In addition, the United States and other countries have ample experience regulating agriculture and forestry for non-NET purposes.

One way to maintain public confidence during rapid deployment of NETs is to invest in a substantial effort to educate the public during the research and development phase. Further, a recent commentary within *Nature* (Lenzi et al., 2018) called for increasing the use of social science to develop assumptions used in models that assess the role of NETs in climate mitigation.

Insufficient Scientific/Technical Understanding

Virtually all approaches to carbon mineralization are limited by insufficient understanding. For example, there is (1) no comprehensive public inventory of appropriate geologic deposits and existing tailings of reactive but unreacted rock, (2) a lack of understanding of the kinetics of CO_2 uptake both at the laboratory scale and in the field, and (3) insufficient technical expertise to manage tailings piles so that they effectively take up CO_2. Negative feedbacks—such as decreases in porosity because of the clogging of pores by carbonate minerals or the coating of reactive surfaces by reaction products—cannot be predicted. In addition, positive feedbacks, such as increasing permeability and reactive surface area via “reaction-driven cracking,” are not well understood. The long-term consequences of depositing crushed reactive minerals in agricultural soils, along beaches, or into the shallow ocean is unknown.

The scientific understanding of coastal blue carbon is at a similar state of development, albeit more advanced for tidal wetlands than for seagrass meadows. The carbon removal caused by restoration and creation of tidal wetlands can be predicted with some confidence. However, the field lacks a mechanistic understanding of the number of critical processes that govern carbon burial and sequestration in coastal ecosystems that may change under high rates of sea level rise and other direct and indirect impacts of climate change, and few studies on transgression of coastal wetlands inland have been conducted. Finally, there are few empirically verified methods to augment carbon removal and sequestration as part of coastal engineering (i.e., coastal adaptation) projects.

Although better understood than the mineralization and coastal options, the other NETs present some knowledge gaps. For example, the field does not fully understand (1) induced seismicity from subsurface injection of CO_2 and (2) the co-benefits of biochar beyond storage, especially whether biochar additions increase the rate of carbon storage in agricultural lands. Agricultural soils methods do not exist for some cropping systems and many grazing systems, particularly in semi-arid rangelands, and it is not obvious that established methods of agricultural soils are optimized in any system.

PROPOSED RESEARCH AGENDA

Scaling the capacity of NETs to address the expected needs for carbon removal will require a concerted research effort to address the constraints that currently limit deployment. The research agenda must address not only potential research gaps, but also other needs for scale-up of NETs, including cost reductions, deployment, and monitoring and verification. The proposed research is divided between (1) projects that would exclusively advance NETs (Table 8.3) and (2) research on biofuels and CO_2 sequestration that would not only advance NETs, but should also be undertaken as part of an emissions mitigation research portfolio (Table 8.4). Drawing on the expertise of certain members, the committee estimated the budget for each research effort. Of course, these budget estimates contain some uncertainty, but there is value in assessing the relative levels of investment needed to advance each of the NETs and sequestration approaches. For example, the estimated research budget for afforestation/reforestation and forest management is lower than that for other NETs because these approaches are more mature. In contrast, the estimated research budgets for carbon mineralization and direct air capture are larger because these technologies are relatively new and underexplored.

The first task in the committee's Statement of Task is "Identify the most urgent unanswered scientific and technical questions needed to assess the benefits, risks, and sustainable scale potential for carbon dioxide removal and sequestration approaches in the terrestrial and nearshore/coastal environment; and increase the commercial viability of carbon dioxide removal and sequestration." The committee used this guidance to strike a balance between research that would provide answers within a decade and those that would take longer to do so. Most of the research will likely pay off fully within 10 years. In contrast, "frontier" research, such as breeding plants whose roots enhance agricultural soil carbon removal and storage or enhanced weathering in situ in ultramafic rock, may not pay off fully for two decades. The committee did not consider very long-term solutions such as increasing the fundamental efficiency of photosynthesis.

The committee's conclusion that afforestation/reforestation, forest management, agricultural soils, and BECCS will be insufficient to achieve the CO_2 removal needed within a generation—because of competing demands for land with food and biodiversity—led to a heavy emphasis on advancing new high-capacity alternatives. Thus, the research plan calls for a large investment in direct air capture, despite its current high cost and expected future cost of not far from \$100/t CO_2, and mineralization as a second option with significant potential. The research plan also includes a substantial investment to increase carbon removal and to understand and perhaps soften the land constraint facing afforestation/reforestation, forest management, agricultural soils, and BECCS. For example, the plan provides \$6-9M/y to further understanding of ways to extend carbon removal to agricultural lands without disrupting food security, as well as \$92-216M/y to reduce both the required land area and cost of BECCS.

Based on its review of the factors that will influence scale-up of NETs, the committee drew the following conclusions that motivate the selection of research priorities:

<u>Conclusion 5:</u> Afforestation/reforestation, agricultural soils, forest management, and BECCS can already be deployed at significant levels, but limited per-hectare rates of carbon uptake by agricultural soils and competition with food and biodiversity for land (for afforestation/reforestation, forest management, and BECCS) will likely limit negative emissions from these options to significantly less than 10 Gt/y CO_2, globally. Research could identify ways to soften the land constraint, for example by developing crop plants that take up and sequester carbon more efficiently in soils, or by reducing demand for meat or food waste. However, crop

TABLE 8.4 Research Plan and Budget for NET-Enabling Research

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
38	BECCS	Biomass-to-power with CCS: Biomass supply and logistics	53-123	5	Improve (1) pretreatment technology for converting biomass into a drop-in replacement for coal and (2) logistics research to address biomass supply chain issues (production, storage, handling, and transportation).	DOE USDA National labs Industry	Cost
39	BECCS	Biomass-to-power with CCS: High efficiency biomass power	39-94	10	Increase the conversion efficiency of biomass to electricity by developing advanced conversion processes and by pretreatment of biomass.	NETL Industry	Cost
40	BECCS	Biomass-to-fuel with CCS	Ongoing research efforts are sufficient		Advance cellulosic ethanol.	DOE	Cost Energy Use
41	Carbon Mineralization	Mine tailings and industrial wastes	1	10	Kiloton to megaton per year field experiments, together with extensive field inventories and laboratory characterization of the reactivity of various potential solid reactants. 4 projects at $250K/y for 10 years.	DOE NSF USGS	Science/ Technical Understanding Cost Energy Use Other Environmental

							Constraints Governance Monitoring and Verification Practical Barriers
42	Carbon Mineralization	Medium-scale field in-situ experiment in a basalt formation.	10	10	Optimization of injection strategies, particularly for shallow reservoirs. Longer duration, higher flux experiments should examine evolution of subsurface reaction fronts, determine the nature of local carbon mineralization reactions, and feedbacks affecting permeability and reactive surface area. $10M/y for 10 years.	DOE NSF USGS	Science/ Technical Understanding Cost Energy Use Other Environmental Constraints Governance Monitoring and Verification Practical Barriers

continued

TABLE 8.4 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
43	Geologic Sequestration: Saline Aquifer Storage	Reduction of seismic risk	50	10	The proposed budget would allow for 3 experiments in different geographic regions of the United States each at a cost of about $15M/y for 10 years. The region-specific projects would be supported by $5M/y of model development, laboratory studies, and analysis of new and existing data sets. This research would improve understanding of and reduce the risks of induced seismicity at geological sequestration sites, develop methods for assessing and mitigating risks of seismicity, improve capacity estimates by screening sites that are high risk for induced seismicity, and help quantify the risk of leakage from fault slippage.	DOE NSF EPA DOI	Science/Technical Understanding Other Environmental Constraints Practical Barriers
44	Geologic Sequestration: Saline Aquifer Storage	Increasing the efficiency and accuracy of site characterization and selection	45	10	Partner with industry to develop and test innovative approaches for characterizing greenfield sites, which usually require on the order of $100M to assess whether a site is suitable.	DOE NSF EPA DOI Industry	Science/Technical Understanding Cost Governance Practical Barriers

					The program could be carried out by expanding the CarbonSAFE program to include 2 sites with sequestration quantities of 200+ Mt CO_2 to assist states and commercial entities in qualifying sites for large-scale deployment (4 projects over a 10-year period). $5M/y of the proposed budget would be used to support academic, national laboratory, and industrial research developing innovative approaches that could be tested in the above-mentioned field programs.		
45	Geologic Sequestration: Saline Aquifer Storage	Improving monitoring and lowering costs for monitoring and verification	50	10	The proposed research program would provide for 4-6 projects at a cost of $5-10M/y. The collaborative projects would develop and demonstrate approaches to optimize integrated monitoring programs that reduce costs while increasing quality and access to real-time information about the status of stored CO_2. In addition to the field experiments, $10M/year would be used to support fundamental research to develop and test new approaches for quantifying mass balances, measuring CO_2 saturations, and quantifying leakage.	DOE NSF EPA DOI	Monitoring and Verification Cost Practical Barriers

continued

TABLE 8.4 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
46	Geologic Sequestration: Saline Aquifer Storage	Improving secondary trapping prediction and methods to accelerate secondary trapping	25	10	This research program would support a 10-year multi-investigator team to perform a large-scale experiment designed to quantify the effectiveness of natural and accelerated trapping for immobilizing CO_2 in the post-injection period. The experiment would require a combination of field experiments, multi-scale laboratory experiments, numerical modeling, and monitoring.	DOE NSF EPA DOI	Science/Technical Understanding Permanence Practical Barriers
47	Geologic Sequestration: Saline Aquifer Storage	Improving simulation models for performance prediction and confirmation	10	10	This program would support 2-3 teams of researchers to develop improved simulation models for predicting the fate and transport of CO_2 in the subsurface, particularly with regards to the effects of geological heterogeneity, secondary trapping mechanisms, geochemical reactions, geomechanical responses to CO_2 injection, and the coupling between them over thousands of years.	DOE NSF EPA DOI	Science/Technical Understanding Permanence

48	Geologic Sequestration: Saline Aquifer Storage	Assessing and managing risk in compromised storage systems	20	10	Improve understanding of the impact of leakage on groundwater systems and the vadose zone. Quantify the extent to which these interactions attenuate CO_2 migration and mitigate risks of leakage to the atmosphere.	DOE NSF EPA DOI	Science/ Technical Understanding Practical Barriers, Permanence
49	Geologic Sequestration: Oil and Gas Field Sequestration	Developing reservoir engineering approaches for co-optimizing CO_2-EOR and sequestration	50	10	Develop and demonstrate reservoir management practices to co-optimize CO_2-EOR and CO_2 sequestration to achieve negative emissions during oilfield operations. Quantify the extent of negative emissions that can be achieved by co-optimization. Two field-scale experiments in partnership with industry are proposed, each with a budget of $20M/y for 10 years. $10M/y will support academic, national laboratory and industry research to develop new approaches for co-optimization.	DOE NSF EPA DOI Industry	Science/ Technical Understanding Practical Barriers

continued

TABLE 8.4 Continued

Item	NET	Research Title	Cost $M/y	Duration Years	Summary	Potential Sponsors and Performers of Research	Barrier(s) Addressed or Frontier
50	Geologic Sequestration	Social sciences research to improve public engagement effectiveness with local communities and the general public	1	10	Establish best practice for community engagement, rules of practice, and regulation guidelines. Provide educational materials for increasing awareness of the need, opportunity, risks, and benefits of geological sequestration for negative emissions.	DOE NSF EPA DOI	Practical Barriers

NOTES: All projects not only should be part of any comprehensive research effort on carbon mitigation, but also would support the advancement of negative emissions methods. BECCS=Bioenergy with Carbon Capture and Storage, CCS=Carbon Capture and Storage, DOE=Department of Energy, DOI=Department of the Interior, EOR=Enhanced Oil Recovery, EPA=Environmental Protection Agency, NSF=National Science Foundation.

improvement is a slow process, while meat consumption and food waste remain high despite health and economic drivers to reduce them.

<u>Conclusion 6:</u> Direct air capture and carbon mineralization have high potential capacity for removing carbon, but direct air capture is currently limited by high cost and carbon mineralization by a lack of fundamental understanding.

<u>Conclusion 7:</u> Although their potential for removing carbon is lower than other negative emissions technologies, coastal blue carbon approaches warrant continued exploration and support. The cost of the carbon removal is low or zero because investments in many coastal blue carbon projects target other benefits such as ecosystem services and coastal adaptation. Understanding of the impacts of sea-level rise, coastal management, and other climate impacts on future uptake rates should be improved.

<u>Conclusion 8:</u> Several carbon mitigation research efforts would also support the advancement of negative emissions technologies. Research on geologic storage of carbon dioxide is critical to improve decarbonization of fossil fuel power plants, and also critical for advancing direct air capture and BECCS. Similarly, research on biofuels would also advance BECCS.

The research recommendations in Tables 8.3 and 8.4 were developed to align with the types of funding currently offered by federal agencies. Exceptions include items 23, 25, 27, and 29, which describe public-private partnerships designed to ensure that the public realizes benefits from its funding of direct air capture start-ups, while protecting the intellectual property that makes those start-ups possible. However, it is worth considering the history of federal incentives for wind and solar electricity and the development of unconventional gas and oil. In these cases, costs dropped dramatically, in part because of decades of subsidies that incentivized private companies to compete on price, before their technologies were competitive in the open marketplace. The benefits to the United States have been extraordinary. Wind and solar are now the cheapest forms of energy in many locations, natural gas is abundant and inexpensive, and the United States is poised to be a major oil exporter. Thus, a historically effective way to reduce the cost of a technology has been to create a competitive market for it by offering financial incentives that make the technology profitable at its current price. This is the theory behind the 45Q tax credit rule.

Which NETs might be ready for such a program? The obvious examples are the NETs with an existing knowledge base to develop a regulatory regime capable of verifying capture and a desired permanence of storage. Examples include most methods of afforestation/reforestation and forest management, some kinds of agricultural soils, such as the use of cover crops and reduced tillage in many cropping systems, electric power BECCS, and direct air capture. Perhaps some forms of mineralization, such as the management of reactive mine tailings, and some coastal options could also be quickly brought to readiness.

RESEARCH BUDGET SUMMARY

The scale of the research budget reflects the size of the carbon and climate problem. A solution such as the one presented in Figure 8.1 is likely to require electricity generated by wind, solar, biomass, nuclear, and natural gas with CCS; biofuels and electricity for transportation; and some form of energy storage. Each of these technologies has received large government investment. For example, Sissine (2014) estimates that the federal government spent more than $22 billion dollars on renewable energy research and development from 1978 to 2013. These investments have paid off spectacularly, with the levelized cost of utility-scale solar and wind electricity now at 3-6¢/kWh (EIA, 2017b). A zero-emitting energy system that costs about what consumers pay today is now technologically feasible because of decades of government investment.

NETs have not yet received comparable public investment despite expectations that they will provide ~30 percent of the net emissions reductions required this century (i.e., maxima of 20 Gt/y CO_2 of negative emissions and 50 Gt/y CO_2 of mitigation in Figure 8.1). NETs are essential to offset emissions that cannot be eliminated, such as a large fraction of agricultural emissions. Low-cost NETs are already less expensive than most forms of mitigation. Direct air capture at a cost of $100/t CO_2 would offset emissions from fossil aviation fuels without affecting food and biodiversity and at a cost comparable to or less than biofuels. Inexpensive direct air capture or carbon mineralization could allow for indefinite use of fossil fuels without climate impacts. The scale of the recommended research budget is consistent both with the need for NETs that can solve a substantial fraction of the climate problem and the possible magnitude of the return to the U.S. economy.

Coastal Blue Carbon

Although coastal blue carbon would be prohibitively expensive if undertaken solely to manage carbon, it is likely that CO_2 removal and/or storage could be added to coastal engineering projects that are undertaken for other reasons (such as storm protection) at zero or low cost. The potential rate of U.S. coastal blue carbon is only about

0.02 Gt/y CO_2, with another 0.01-0.03 Gt/y CO_2 of storage that could be achieved by using organic materials in coastal engineering projects (but the carbon would need to be captured elsewhere). Even at a low average carbon removal and storage cost of \$20/t CO_2, achieving 0.06 Gt/y CO_2 at zero cost would represent a savings of \$200M/y. This calculation justifies the research expenditures proposed in Table 8.3. The core of the proposal for coastal blue carbon is item 3, which calls for \$40M/y for 20 years to establish and operate a network of research sites. These would straddle edaphic gradients and include both natural systems and those undergoing coastal engineering projects. A common set of measurements across the network would advance our understanding of carbon removal and storage in coastal ecosystems, and experiments would determine how best to add carbon removal and storage to coastal engineering projects at the lowest cost. The plan also calls for \$6M/y for 5-10 years for basic research (item 1), \$2M/y for 20 years to map and monitor coastal wetlands (item 2), \$2M/y for 20 years for a data center (item 4), and \$5M/y for 10 years for social science research on cost-effective adaptive management of coastal blue carbon and on the response of coastal land owners and managers to carbon removal and storage incentives (item 6). The social science research would also investigate policies to manage responsibility for carbon lost to inundation or erosion.

A broad range of federal, state, and local government agencies and academic institutions comprise potential funding opportunities for coastal blue carbon research. These include, for example, the National Science Foundation (NSF), Department of Energy (DOE), EPA, National Aeronautics and Space Administration, U.S. Army Corps of Engineers, and National Oceanic and Atmospheric Administration. An interagency–academia–nongovernmental organization–industry program work group would also be useful, particularly for the development of a comprehensive coastal blue carbon projects database. In addition, foundations and the private sector have important roles to play in research related to demonstration and deployment of coastal blue carbon and storage projects.

Afforestation/Reforestation and Forest Management

The research budget for afforestation/reforestation and forest management is relatively low because this is a relatively mature area. The field holds great promise for carbon removal and sequestration because (1) for more than a century, foresters have researched how to maximize wood production, including developing tree varieties that grow quickly; (2) wood is about 50 percent carbon; and (3) most temperate and tropical forests store most of their carbon in wood. The total research effort to accomplish something very close to forest carbon removal and sequestration has already been very large. To cite just one example, the U.S. Forest Service (USFS) Forest Inventory and Analysis (FIA) Program spends $70M/y measuring U.S. wood biomass and changes in biomass in ~100,000 repeatedly censused plots. The largest forest-related expenditure in Table 8.3 (item 8, $3.7-14M/y for 10 years) is shared with BECCS. The effort to improve humanity's understanding of the land-area constraint facing afforestation/reforestation, forest management approaches, and BECCS might allow increased carbon removal in all of these categories, and if not, might still reduce the probability of making a grave policy error. The proposed expenditure on IAM of land-use change is not larger because the committee believes that genuine understanding in this area is likely to improve only slowly. This also explains the 10-year proposed duration of the funding. Items 7 and 12 in Table 8.3 leverage substantial other investments by USFS. Item 10, if successful, could provide a very large benefit at very low cost (see Chapter 3).

USFS has a central role in furthering research and funding for afforestation and forest management, while USDA and NSF are well suited to carry out research on social science topics and other environmental and societal impacts.

Uptake and Storage by Agricultural Soils

The cost of the research on carbon removal and storage by agricultural soils is intermediate relative to the research budget for other NETs. Unlike foresters, agricultural plant breeders have not focused specifically on aspects of plant productivity that would increase carbon removal and storage (i.e., above-ground biomass for trees, but deep and difficult to decompose roots for agricultural crops). Thus, $40-50M/y of the budget is for development of new agricultural varieties (item 17 in Table 8.3). The 20-year duration in the plan reflects the need for a sustained effort. This would expand the considerable investment in this area by the Advanced Research Projects Agency-Energy (ARPA-E). Despite the lack of breeding to enhance carbon removal and storage, agricultural scientists still know how to accomplish these goals in most cropping systems and some grazing systems because soil carbon is a measure of soil health, which they have worked to improve for decades. The second largest portion of the plan, items 13 and 14 ($11-14M/y), is critical to extend carbon storage practices to cropping systems where previous work has been insufficient, and to increase efficiency and reduce costs in all areas. This expenditure will also improve agricultural productivity and nitrogen- and water-use efficiency and could be justified because of these benefits alone. Item 19 is critical to develop both cost-competitive biofuels and biofuels with net negative emissions (fuels-BECCS). Finally, item 18 might provide large new capability at low cost. Collectively, the three "frontier" items (17,18, and 19) might double the potential for storage in agricultural soils or more. Item 20 is discussed with the carbon mineralization options below.

Programs within USDA, NSF, and/or DOE have the most appropriate infrastructure to conduct research on topics pertaining to agricultural soils. Land-grant universities also have an important role to play, for example, by conducting experiments for the evaluation of region-specific best management practices for soil carbon sequestration. In addition, the USDA/Natural Resource Conservation Service's Conservation Innovation Grants can provide needed empirical knowledge on topics in economic and behavioral research along with the continuation and expansion of pilot emission reduction and carbon removal and storage projects.

Bioenergy with Carbon Capture and Storage

BECCS-to-fuels offers (1) the greatest opportunity for the development of new cost-competitive biofuels, (2) the possibility that these could be produced with net negative emissions, and (3) a possible benefit for agricultural productivity (through the application of biochar). These are the reasons for the recommended investment in a comprehensive development push in this area for 10 years (item 21). The economic and energy security benefits from this investment might be speculative, while the CO_2 removal and storage benefits are likely to be material, but still constrained by available waste biomass. Table 8.4 also proposes research for improving the productivity and density of energy crops used in electricity generation, and for research to increase the conversion efficiency of biofuels to electric power. Although this should be considered as part of the nation's biofuels research budget, it is included here because the possibility of improved BECCS provides another justification for it.

The BECCS research agenda also includes the development of a life cycle analysis-based framework to compare NETs in the United States. Although it is applicable to all NETs, it was included as part of the BECCS research agenda because BECCS is so complex, which makes it very difficult to determine net CO_2 removal. This is much more straightforward for afforestation/reforestation, agricultural soils, coastal blue carbon, direct air capture, and even carbon mineralization.

Several agencies within USDA, DOE, and EPA are active in and capable of effectively carrying out most of the proposed basic and applied research components and tasks for BECCS. However, they may not be currently equipped to effectively run a technology demonstration program. Public-private partnership entities have historically played substantial roles in the demonstration and deployment of new technology. As such, the evaluation of existing government agency technology demonstration capabilities and the investigation of institutional structures that will have the capabilities needed to effectively develop and demonstrate new biomass energy technology is critical to successful scale-up and deployment of new technologies.

Direct Air Capture

The direct air capture budget was formulated to provide a substantial chance of developing ~\$100/tCO$_2$ direct air capture and sequestration within one or two decades. The challenge of direct air capture development is that no commercial driver for the activity exists in the absence of a high carbon price (unlike afforestation/reforestation, agricultural soils, BECCS-to-fuels, and coastal blue carbon). For this reason, the development of a practical direct air capture option will require sustained government investment. However, the committee also concluded that progress would be most likely if a cooperating and competing ecosystem of researchers and start-ups could explore the many options for direct air capture and advance many dimensions of the technology at once. The plan and budget cover four separate stages of technology development. The effort by multiple researchers and companies at each stage is paired with work by a National Direct Air Capture Test Center, that would facilitate research (i.e., provide techno-economic analysis and engineering design help), conduct measurements of each entity's technology using a common basis for comparison, and disseminate public information while protecting intellectual property. The first stage (items 22 and 23 and \$23-35M/y for 10 years) would search for better materials and component designs with many \$1 million efforts. The second (items 24 and 25 and \$13-25M/y for 10 years) would scale up new materials and components so that they could be produced at the scale necessary for a pilot plant (>1,000 t CO$_2$/y). The third (items 26 and 27 and \$30-60M/y for 10 years), would build and evaluate \$20M/project pilot plants. The fourth (items 28 and 29 and \$115-120M/y for 10 years) would provide the final scale-up to >10,000 t CO$_2$/y at \$100M/project. Obviously, stages 1-4 would not run either entirely in parallel or entirely sequentially. Most groups would enter the program at stage 1, some at stage 2, and maybe one or two at stage 3. If successful, the effort would deliver commercial-scale direct air capture at greatly reduced price within 10-20 years.

DOE's Office of Fossil Energy and National Energy Technology Laboratory (NETL) have the appropriate infrastructure to manage direct air capture research, development, and demonstration projects through typical proposal and grant processes for distribution of funding to universities, nonprofit research organizations, start-up companies, and large companies. DOE's existing infrastructure can also manage contractors for independent materials testing, component testing, techno-economic analysis, and professional engineering design. A centralized facility/national testbed similar to the NETL's National Carbon Capture would be appropriate for development and demonstration testing of direct air capture components and systems. Moreover, contracting mechanisms, such as fixed-fee or cost-plus contracts, would prove useful for developing direct air capture technology. However, no public investments should be made without first identifying a clear market incentive for carbon removal; in the absence of a market incentive for carbon removal, industry will not invest in the commercial deployment of direct air capture systems.

Carbon Mineralization

The committee recommends a substantial investment in new carbon mineralization research because carbon mineralization would have effectively unlimited capacity if cost-effective methods could be found, and because early work is encouraging. The plan calls for basic research on the kinetics of carbon capture by minerals ($5.5M/y for 10 years, item 30) and on feedbacks between reaction and fluid flow for in situ applications ($17M/y for 10 years, item 31). It includes an effort to map near-surface formations and existing tailings piles of reactive minerals by the U.S. Geological Service (USGS) at $7.5M/y (item 32) and $3.5M/y for 10 years (item 33) to explore enhanced weathering of reactive surficial deposits in mine tailings and other locations. It includes $3M/y for 10 years for experimental studies of the addition of reactive minerals to agricultural soils (item 20). The most ambitious project is to explore the possibility of in situ CO_2 removal and sequestration in formations of near-surface ultramafic rock (averaging $10M/y for 10 years, item 34). Table 8.4 also contains two sequestration-only mitigation projects. The first is to attempt to store captured CO_2 in reactive mine tailings ($1M/y for 10 years, item 41). Although the mass of existing tailings and their annual rate of production are relatively small (enough to store tens of Mt CO_2), the costs could be as low as $10/t CO_2. Item 42 proposes a medium-scale injection of CO_2 into a basalt formation to provide an alternative to saline aquifer storage (averaging $10M/y for 10 years). This is the next step, given previous efforts in Washington State (~1,000 t CO_2) and Iceland (order of 10,000 t/y CO_2 for several years).

Much of the recommended research for carbon mineralization falls within the domains of the NSF Directorate for Geosciences, USGS, and DOE. Several programs within DOE (e.g., Basic Energy Sciences Program and Office of Fossil Energy, combined with the Crosscutting Subsurface Technology and Engineering Research, Development, & Demonstration [SubTER] initiative) hold the potential for funding research on the overall topic of kinetics and other aspects of carbon mineralization. University research in the theoretical aspects of carbon mineralization research will be key, and an explicit NSF partnership to fund greenhouse gas mitigation research would be useful. Such a partnership could resemble several successful initiatives within NSF's Directorate for Geosciences, such as the RIDGE, MARGINS, and GeoPRISMS Programs.

Geologic Sequestration in Saline Aquifers

Table 8.4 proposes new research on safe and cost-effective sequestration of CO_2 in saline aquifers. This is a national budget to support a relatively mature field that is already practiced at large scale (approaching 100 Mt/y CO_2) and that is now subsidized by the U.S. government at \$50/t CO_2. Saline aquifer storage is vital to mitigate fossil power emissions and to make direct air capture and BECCS carbon negative. The proposed research plan includes \$50M/y to reduce risks of induced seismicity (item 43), \$45M/y to increase the efficiency and accuracy of site characterization and selection (item 44), \$50M/y to improve and reduce the cost of monitoring and verification (item 45), \$25M/y to improve secondary trapping of CO_2 (item 46), \$10M/y to improve simulation modeling (item 47), \$20M/y to research ways to manage the risk of leakage of CO_2 to the atmosphere and groundwater (item 48), and \$50M/y to develop methods that co-optimize enhanced oil recovery and carbon sequestration (item 49).

DOE, NSF, EPA, and the Department of the Interior (DOI) all have important roles in continued funding and research on geological sequestration. For example, new research and development needs in DOE's purview include research on trapping mechanisms as well as multiscale, multiphysics modeling of the fate and transport of CO_2 in the subsurface. NSF plays an important role in engaging and leveraging university research on Earth processes that are relevant to sequestration. EPA could collaborate with DOE and DOI to support the development of reliable approaches regarding contamination sequestration sites. Both USGS and the Bureau of Land Management (BLM) are well suited to further the scale-up of geological sequestration.

CONCLUSION

Every recent analysis of solutions to the climate problem has concluded that NETs should play as large a role as any mitigation technology, with 10 Gt/y CO_2 of negative emissions needed by midcentury and 20 Gt/y CO_2 by the century's end. Several Gt/y CO_2 of negative emissions at less than \$20/t CO_2 are already available, and afforestation/reforestation negative emissions have been part of the United Nations Framework Convention on Climate Change (UNFCCC) for more than a decade. Existing agricultural soils methods have large co-benefits that would improve the productivity and economic resilience of U.S. farms, even without the carbon benefit. Nonetheless, existing options (coastal blue carbon, afforestation/reforestation, forest management, agricultural soils, and BECCS) cannot yet provide enough negative emissions at reasonable cost, without substantial unintended harm to the global food supply and environment. A substantial research investment is needed to improve existing NETs and to reduce their costs. In addition, two options with essentially unlimited capacity have remained substantially less explored than the other NETs. An investment in direct air capture and carbon mineralization research by the United States has the potential to revolutionize the future evolution of our energy system.

> **Recommendation: The nation should launch a substantial research initiative to advance negative emissions technologies (NETs) as soon as practicable. A substantial investment would (1) improve existing NETs (i.e., coastal blue carbon, afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and bioenergy with carbon capture and sequestration) to increase the capacity and to reduce their negative impacts and costs; (2) make rapid progress on direct air capture and carbon mineralization technologies, which are underexplored, but would have essentially unlimited capacity if the high costs and many unknowns could be overcome; and (3) advance NET-enabling research on biofuels and carbon sequestration that should be undertaken anyway as part of an emissions mitigation research portfolio.**

Glossary

Afforestation	Planting forest on lands that were originally grasslands or shrublands.
Avoided emissions	Greenhouse gas emissions reductions resulting from the avoidance or reduction of an emitting activity (e.g., preventing deforestation).
Biochar	A solid carbon product of biomass thermochemical conversion.
Brucite	Magnesium hydroxide mineral, $Mg(OH)_2$, commonly formed together with *serpentine* during hydration of *ultramafic* rocks.
Calciner	A kiln where calcium carbonate is heated with natural gas to produce solid calcium oxide in a direct air capture liquid solvent system.
Capillary or residual gas trapping	Immobilization of CO_2 as a result of interaction with pore space in a geologic storage reservoir.
Carbon dioxide removal	Intentional efforts to remove carbon dioxide from the atmosphere. Such efforts complement carbon capture and sequestration methods that primarily focus on reducing CO_2 emissions from point sources such as fossil fuel power plants.
Carbonates	Minerals such as *magnesite* ($MgCO_3$), *calcite* ($CaCO_3$) and *dolomite* ($MgCa(CO_3)_2$). Formation of *carbonate* minerals by reaction of CO_2 with Mg- and Ca-bearing silicates is commonly called *carbonation* and *carbon mineralization.*
Causticizer	A reactor where calcium carbonate is precipitated in a liquid solvent direct air capture system.
CO_2e	A unit of measure of the amount of CO_2 that would have an equivalent global warming impact as a greenhouse gas of interest.

Combustion	The most oxidizer-enriched of the thermochemical conversion paths, where sufficient oxidizer such as air or oxygen is provided to ensure complete oxidation of biomass for the production of power and/or heat.
Crust	Relatively low density, SiO_2-rich, uppermost layer of the solid Earth; *oceanic crust* is mafic and about 7 km thick; *continental crust* is *intermediate* to *felsic*, with more Si, Al, Na, K than *oceanic crust*, and a variable thickness averaging ~36 km.
Exergy	The capacity of energy to do physical work.
Gasification	A process where a gasifying agent such as steam, air, or CO_2 is used to partially oxidize biomass and produce high yields of combustible gases.
Hydrothermal liquefaction	A thermochemical process where biomass is converted to produce predominantly liquids via heating in water, where the water acts as a reactant.
Integrated assessment modeling	A quantitative tool for combining diverse fields (i.e., science, economics, and policy) to assess an impact, in this case the impact of emissions or emissions reductions.
Levelized cost of energy	The net present value of energy production over the lifetime of the generating source.
Life cycle analysis or life cycle assessment	An assessment of all of the environmental impacts over the lifetime of a product, from raw material to consumption.
Listvenite	Rock composed of *carbonate* minerals + *quartz* + Fe-oxides + Cr-rich oxides or silicates, produced by complete *carbonation* of *peridotite*, in which all Mg and Ca combine with CO_2 to form *carbonate* minerals, most Fe forms oxides, and all SiO_2 forms *quartz*.
Mafic	Rock containing ~45-53 wt% SiO2 and/or composed of >10 wt% Ca-rich plagioclase (>50% An), typically with *olivine*, *pyroxenes,* and amphiboles, and no *quartz*. Mafic lavas are *basalts*. Mafic plutonic rocks are *gabbros* (*sensu lato*). Some *mafic* intrusions host significant ore deposits (Ni, Cr, platinum group elements). *Gabbroic* rocks with very abundant *plagioclase* are called *anorthosites*.

Mantle	Relatively dense, *ultramafic* layer of the solid Earth, underlying the crust. The upper *mantle*—from the base of the *crust* to ~410 km depth—is composed of *peridotite* and contains abundant Mg-rich *olivine*.
Negative emissions technology	An approach that removes CO_2 from the atmosphere to be sequestered.
Olivine	Mineral solid solution between endmembers *forsterite* (Mg_2SiO_4) and *fayalite* (Fe_2SiO_4). *Olivine* comprises more than 60% of Earth's upper *mantle*, where it is > 88% *forsterite*.
Ophiolite	Block of *oceanic crust* and upper *mantle,* an oceanic plate, thrust onto a continental margin.
Peridotite	*Ultramafic* rock containing greater than 40% *olivine* (aka the gemstone "peridot"). *Peridotite* comprises most of Earth's upper *mantle*.
Plagioclase	A solid solution mineral, part of the feldspar group, with compositions ranging continuously from *anorthite* (An, $CaAl_2Si_2O_8$) to *albite* (Ab, $NaAlSi_3O_8$), including *bytownite* (Byt, 70-90% An), *labradorite* (Lab, 50-70% An), *andesine* (30-50% An) and *oligoclase* (10-30% An). *Plagioclase*, particularly *labradorite*, is a common constituent of crystalline *basalt* (mantle-derived lava) and its slowly cooled, plutonic equivalent *gabbro*, together with ~0-20% *olivine* and 0-40% *pyroxenes*.
Progradation	Sediment deposition in wetlands that results in lateral of growth of the seaward edge.
Pyrolysis	A highly oxidizer deficient or anoxic thermochemical process in which biomass is heated in the absence of air to produce liquids and gases, which may be upgraded to biofuels or directly combusted, and solid carbon-rich biochar, which may be combusted, gasified, or distributed in soil for storage and soil amendment
Pyroxene	Fe-Mg silicates including *orthopyroxene*, with Mg-endmember *enstatite* (En, $Mg_2Si_2O_6$), and *calcium-rich pyroxene* with Mg-endmember *diopside* (Di, $CaMgSi_2O_6$). Mg-rich *pyroxenes* comprise 0-40% of mantle *peridotites*. Rocks with

	greater than 60% *pyroxene* with less than 10% feldspar are *pyroxenites*.
Quartz	SiO_2 mineral.
Reforestation	Planting forest on lands that used to be forest, but were converted to another use.
Serpentine	Hydrous silicate minerals with Mg-endmembers $Mg_3Si_2O_5(OH)_4$. Formation of *serpentine* plus other minerals by hydration of *ultramafic* rocks is often called *serpentinization*. Rocks composed mainly of serpentine are called *serpentinites*. Polytypes of serpentine include *chrysotile*, *lizardite,* and *antigorite*. *Chrysotile* and *lizardite* are common products of low-temperature hydration of *ultramafic* rocks and of *olivine* and *pyroxene* in *mafic* rocks.
Slaker	A reactor where calcium oxide reacts with water to regenerate calcium oxide for reuse in a causticizer as part of a liquid solvent direct air capture system.
Solid sorbent	The capture surface for direct air capture systems utilizing adsoption and desorption to a CO_2-sorbent material.
Solubility trapping	Secondary trapping mechanism for geologic storage resulting from dissolution of CO_2 into an aquifer.
Spreading ridge	Narrow zone of extension and formation of new, igneous *oceanic crust* from *basaltic* partial melts of the upper *mantle* rising between two diverging tectonic plates.
Subduction zone	Thrust fault at zone of convergence between two tectonic plates where one plate is thrust beneath the other; typically, old *oceanic crust* is thrust into the *mantle.*
Supercritical CO_2	CO_2 gas compressed to a fluid above its critical temperature and pressure.
Transgression (of wetlands)	Migration of a tidal wetland into adjacent uplands as sea levels rise.
Ultramafic	Rock containing < 45 wt% SiO_2 and > 18 wt% MgO, and/or composed of > 90 wt% "mafic minerals," which are *olivine*, *pyroxenes*, amphiboles, and *serpentines*. *Ultramafic*

	rocks including *peridotite* comprise most of Earth's upper *mantle* to a depth of about 410 km below the surface, and also form igneous rocks that host significant ore deposits, including explosively emplaced *kimberlites* (diamonds), igneous intrusions including *peridotites and pyroxenites* (Ni, Cr, platinum group elements), and ultramafic lavas known as *komatiites* (Ni).
Wollastonite	Ca-silicate mineral $CaSiO_3$ most commonly found where granitic intrusions reacted with limestones.

Acronyms and Abbreviations

A&E	architecture and engineering
ACR	American Carbon Registry
ADM	Archer Daniels Midland
AFRI	Agriculture and Food Research Initiative
APS	American Physical Society
ARPA-E	Advanced Research Projects Agency-Energy
ARS	Agricultural Research Service
ASU	air separation unit
BECCS	bioenergy with carbon capture and sequestration
BLM	Bureau of Land Management
CAP	Coordinated Agricultural Project
CAPEX	capital expenditure
CAR	Climate Action Reserve
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CAST	Council on Agricultural Science and Technology
C-CAP	Coastal Change Analysis Program
CCIWG	Carbon Cycle Interagency Working Group
CCS	carbon capture and sequestration
CCUS	carbon capture, utilization, and storage
CDCL	coal direct chemical looping
CKD	cement kiln dust
CMS	carbon monitoring system
CO_2	carbon dioxide
CRI	CRI Catalyst Company, Shell Group
CRMS	Coastwide Reference Monitoring System
CRP	Conservation Reserve Program
CSP	Conservation Stewardship Program
CWPPRA	Coastal Wetlands Planning, Protection, and Restoration Act
DEB	Division of Environmental Biology
DOE	Department of Energy
DOI	Department of the Interior

EIA	Energy Information Administration
EJ	exajoule
ENSO	El Niño–Southern Oscillation
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FA	fly ash
FE	fossil energy
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FIA	Forest Inventory and Analysis
FTE	full-time equivalent
GCEP	Global Climate and Energy Project
GDP	gross domestic product
GeoPRISMS	Geodynamic Processes at Rifting and Subducting Margins
GHG	greenhouse gas
GRI	Gas Research Institute
GTI	Gas Technology Institute
ha	hectare
IAM	integrated assessment model
IECM	integrated environment control model
IGCC	integrated gasificaton combined cycle
IL-ICCS	Illnois Industrial Carbon Capture and Storage
INDC	intended nationally determined contribution
InSAR	interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
ISBL	inside battery limits
ITM	Inland Testing Manual
JPL	Jet Propulsion Laboratory
KIIT	Korea Institute of Industrial Technology
LCA	life cycle assessment
LCOE	levelized cost of electricity

LHV	lower heating value
LTER	Long-Term Ecological Research
MEA	monoethanolamine
Mha	million hectare
MHHW	mean higher high water
MHHWS	Mean Higher High Water Spring
MLW	mean low water
MMT	million metric tons
MMW	measuring, monitoring, and verification
MSL	mean sea level
MTG	methanol-to-gas
MVA	monitoring, verification, accounting
N_2O	nitrous oxide
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NBBF	natural and nature-based features
NCPV	National Center for Photovoltaics
NEON	National Ecological Observatory Network
NEP	net ecosystem productivity
NERRA	National Estuarine Research Reserve Association
NET	Negative Emissions Technology
NETL	National Energy Technology Laboratory
NGCC	natural gas combined cycle
NGO	nongovernmental organization
NIFA	National Institute of Food Agriculture
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
NREL	National Renewable Energy Laboratory
NRI	Natural Resource Inventory
NSF	National Science Foundation
NSF OCE	National Science Foundation Division of Ocean Studies
O&M	operations and maintenance
OC	organic carbon
OTM and ITM	Ocean and Inland Testing Manuals

PAF	perturbation atmospheric fraction
PNNL	Pacific Northwest National Laboratory
ppm	parts per million
ppmv	parts per million by volume
PSII	photosystem II
PV	photovoltaics
R&D	research and Development
RCP	Representative Concentration Pathway
Re	respiration
REDD+	Reduced Deforestation and Forest Degradation Plus
RIIHL	Reliance Industrial Investments and Holdings Ltd.
ROOTS	Rhizosphere Observations Optimizing Terrestrial Sequestration
RSLR	relative sea level rise
SCPC	supercritical pulverized coal
SCS	soil carbon sequestration
SE	standard error
SET	surface elevation table
SLR	sea-level rise
SOCCR-2	Second State of the Carbon Cycle Report
SOM	soil organic matter
SubTER	Subsurface Technology and Engineering Research, Development, & Demonstration
TRL	technology readiness level
TSA	temperature swing adsorption
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USACE	U.S. Army Corps of Engineers
USC	ultra-supercritical
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VCS	Verified Carbon Standard
VSA	vacuum swing adsorption

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APPENDIX A

Committee Bios

Stephen Pacala (Chair), Princeton University

Dr. Stephen Pacala is Frederick D. Petrie Professor of Ecology and Evolutionary Biology at Princeton University. Currently, he co-directs Princeton's Carbon Mitigation Initiative, which is a collaboration between Princeton University and British Petroleum to find solutions to the problem of global warming. Dr. Pacala previously acted as the director of the Princeton Environmental Institute. His research covers a wide variety of ecological and mathematical topics with an emphasis on interactions between greenhouse gases, climate, and the biosphere. Dr. Pacala earned an undergraduate degree from Dartmouth College in 1978 and a Ph.D. in biology from Stanford University in 1982. He serves on the board of the Environmental Defense Fund. Among his many honors are the David Starr Jordan Prize and the George Mercer Award of the Ecological Society of America. Dr. Pacala is a member of the American Academy of Arts and Sciences and the National Academy of Sciences.

Mahdi Al-Kaisi, Iowa State University

Dr. Mahdi Al-Kaisi is a professor of soil physics in the Department of Agronomy at Iowa State University. Dr. Al-Kaisi received his M.S. and Ph.D. in soil physics from North Dakota State University in 1982 and 1986, respectively. Dr. Al-Kaisi has been on the faculty at Iowa State University since 2000, where his research focuses on the effects of cropping and tillage systems, crop residue management, cover crops, and nitrogen application on soil carbon dynamics and sequestration, greenhouse gas emissions, and other ecosystem services. In addition, he studies the interaction effects of agricultural practices and environmental factors, such as weather variability and landscape spatial variability on soil organic carbon sequestration and systems sustainability and productivity. The focus of his research is to develop sustainable management practices that improve soil health, productivity, and environmental services. As a result of his research, he has developed field calculators to assess soil management practices impacts, such as tillage systems, crop residue, and crop rotation effects on soil sustainability. In addition, he developed a soil carbon index for soils in Iowa.

Mark A. Barteau, Texas A&M University

Dr. Mark A. Barteau is vice president for research at Texas A&M University. He holds academic appointments at Texas A&M in the Department of Chemical Engineering, College of Engineering, and the Department of Chemistry, College of Science. He previously served at the University of Michigan as director of the Energy Institute and the inaugural DTE Energy Professor of Advanced Energy Research, and, prior to joining the University of Michigan, as the senior vice provost for research and strategic initiatives at the University of Delaware. He was elected to the National Academy of Engineering in 2006. Dr. Barteau brings extensive experience as a researcher, inventor, academic leader, and consultant for both U.S. and international organizations. His research focuses on chemical reactions at solid surfaces and their applications in heterogeneous catalysis and energy processes. His research has been funded by the National Science Foundation, the Department of Energy, the Air Force Office of Scientific Research and NASA. Dr. Barteau received his Ph.D. and master's degrees in chemical engineering from Stanford University in 1981 and 1977, respectively.

Erica Belmont, University of Wyoming

Dr. Erica Belmont is currently serving as an assistant professor of mechanical engineering in the College of Engineering and Applied Science at the University of Wyoming. Dr. Belmont is also the principal investigator of the Belmont Energy Research Group. She received her B.S. in chemical engineering and M.S. in mechanical engineering from Tufts University in Medford, Massachusetts, and her Ph.D. in mechanical engineering from the University of Texas at Austin. Her research interests are in combustion, solid fuels (coal, biomass), alternative fuels, renewable energy, and experimentation.

Sally M. Benson, Stanford University

Dr. Sally M. Benson joined Stanford University as a professor in 2007. She holds three appointments at Stanford: professor of energy resources engineering in the School of Earth, Energy and Environmental Sciences; co-director of the Precourt Institute for Energy, the campus-wide hub of energy research and education; and director of the Global Climate and Energy Project (GCEP). Dr. Benson received a B.S. in geology from Barnard College at Columbia University in 1977, and an M.S. and Ph.D. in materials science and mineral engineering from the University of California, Berkeley in 1988. An internationally recognized scientist, Dr. Benson is responsible for fostering cross-campus collaborations on energy and guiding the growth and development of a diverse research portfolio. Prior to joining Stanford, Dr. Benson was at Lawrence

Berkeley National Laboratory. Dr. Benson is a groundwater hydrologist and reservoir engineer and is regarded as a leading authority on carbon capture and storage, and emerging energy technologies. In 2012, she served as a convening lead author of the Global Energy Assessment, a multinational project coordinated by the International Institute for Applied Systems Analysis.

Richard Birdsey, Woods Hole Research Center

Dr. Richard Birdsey is a specialist in quantitative methods for large-scale forest inventories and has pioneered development of methods to estimate national carbon budgets for forestlands from forest inventory data. Dr. Birdsey is currently serving as a senior scientist at the Woods Hole Research Center after recently retiring from the U.S. Forest Service as a "Distinguished Scientist" and was the program manager for global change research in the Northern Research Station. Dr. Birdsey was a lead author of two special reports for the Intergovernmental Panel on Climate Change (IPCC). He was a lead author of the first North American "State of the Carbon Cycle" report and is currently a member of the science team guiding the second report. He has contributed to several assessments of climate change in the United States. He served 3 years as chair of the U.S. Government Carbon Cycle Science Steering Group. He has published extensively on forest management and strategies to increase carbon sequestration and facilitated the development of decision-support tools for policy and management. He was recognized by the U.S. Department of Agriculture as a major contributor to creating a new agricultural commodity—carbon. Dr. Birdsey is a member of a team of scientists developing and implementing the North American Carbon Program, an international effort to improve quantification and understand causes of carbon exchange between land, atmosphere, and oceans. In recent years he has been actively working with Mexico and Canada to improve monitoring, verification, and reporting to support climate change mitigation with an emphasis on Reducing Deforestation and Forest Degradation and promoting sustainable forest management (REDD+) and improving forest management in the three countries. He is currently working with the U.S. Forest Service National Forest System to implement carbon assessments for all of the U.S. National Forests.

Dane Boysen, Modular Chemical, Inc.

Dr. Dane Boysen is CEO of Modular Chemical, Inc. Previously, he was chief technologist for Cyclotron Road, a lab-embedded mentorship program at Lawrence Berkeley National Laboratory funded by the Advanced Manufacturing Office at the U.S. Department of Energy. Prior to Cyclotron Road, Dr. Boysen was the executive director of research operations at the Gas Technology Institute (GTI). Before GTI, he served as a program director at the Advanced Research Projects Agency-Energy (ARPA-E), where he managed more than $100 million over 30 of the nation's most cutting-edge energy technology research and development projects. Prior to joining ARPA-E, Dr. Boysen led an $11 million project to develop liquid metal batteries for grid-scale energy storage under Professor Don Sadoway at MIT. Dr. Boysen co-founded Superprotonic Inc., a venture capital–backed start-up developing solid acid electrolyte-based fuel cells. Dr. Boysen received his M.S. and Ph.D. in materials science at the California Institute of Technology in 1999 and 2001, respectively. Dr. Boysen's research experience includes developing and commercializing hard energy technology.

Riley Duren, Jet Propulsion Laboratory

Mr. Riley Duren is chief systems engineer for the Earth Science and Technology Directorate at NASA's Jet Propulsion Laboratory (JPL). He received his B.S. in electrical engineering from Auburn University in 1992. He has worked at the intersection of engineering and science including seven space missions ranging from earth science to astrophysics. His current portfolio spans JPL's earth system science enterprise as well as applying the discipline of systems engineering to climate change decision-support. His research includes anthropogenic carbon emissions and working with diverse stakeholders to develop policy-relevant monitoring systems. He is principal investigator for five projects involving anthropogenic carbon dioxide (CO_2) and methane emissions. He has also co-led studies on geoengineering research, monitoring, and risk assessment. He is a visiting researcher at University of California, Los Angeles's Joint Institute for Regional Earth System Science and Engineering and serves on the Advisory Board for New York University's Center for Urban Science and Progress.

Charles Hopkinson, University of Georgia

Dr. Charles Hopkinson is a professor of marine sciences at the University of Georgia. Dr. Hopkinson earned both his Ph.D. and M.S. in marine science from Louisiana State University in 1979 and 1973, respectively. Dr. Hopkinson served as a chairman of the Radiation Safety Committee of the Marine Biological Laboratory in Woods Hole, Massachusetts, from 1993 to 2008. Dr. Hopkinson is currently a member of the American Society of Limnology and Oceanography and the Coastal and Estuarine Research Federation. Dr. Hopkinson's current research interests are in the biogeochemistry of watersheds, wetlands, estuaries, and continental shelves as well as climate change and land/sea coupling.

Christopher Jones, Georgia Institute of Technology

Dr. Christopher Jones is a Love Family Professor of Chemical and Biomolecular Engineering in the School of Chemical and Biomolecular Engineering at Georgia Tech. Dr. Jones earned his M.S. and Ph.D. degrees in chemical engineering at the California Institute of Technology in 1997 and 1999, respectively. Dr. Jones was named the associate vice president for research at Georgia Tech in November 2013. In this role, he directs 50 percent of his time on campus-wide research administration, managing internally funded research programs in coordination with the colleges and with a primary focus on interdisciplinary research efforts and policy related to research institutes, centers, and research core facilities. Dr. Jones directs a research program focused primarily on catalysis and CO_2 separation, sequestration and utilization.

Peter Kelemen, Columbia University

Dr. Peter Kelemen is Arthur D. Storke Professor and Chair of the Department of Earth and Environmental Sciences at Columbia University. Dr. Kelemen received his Ph.D. and M.S. from the University of Washington in 1987 and 1985, respectively. Dr. Kelemen is a member of the National Academy of Sciences. He is a fellow of the American Geophysical Union, the Geochemical Society and European Association of Geochemistry, and the Mineralogical Society of America. He is a research associate at the American Museum of Natural History, and an adjunct scientist at the Woods Hole Oceanographic Institute, where he was a senior scientist and Charles Francis Adams Chair until 2004. He has worked on the genesis and evolution of oceanic and continental crust, chemical cycles in subduction zones, and new mechanisms for earthquake initiation. His primary focus is on geologic capture and storage of CO_2 (CCS) and reaction-driven cracking processes in natural and engineered settings, with application to CCS, geothermal power generation, hydrocarbon extraction, and in situ mining, and most recently included CO_2 capture and storage and mineral carbonation and hydration.

Annie Levasseur, École de Technologie Supérieure

Dr. Annie Levasseur is a professor in the Department of Construction Engineering at École de Technologie Supérieure. Dr. Levasseur received her Ph.D. in chemical engineering from Polytechnique Montréal in 2011 and is currently the chair of the United Nations Environment Programme (UNEP) - Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Impact Assessment (LCIA) Global Guidance–Global Warming Task Force, a group of international climate and life cycle assessment (LCA) researchers working to develop guidelines for the use of climate metrics in LCA.

Keith Paustian, Colorado State University

Dr. Keith Paustian is professor in the Department of Soil and Crop Sciences and senior research scientist at the Natural Resource Ecology Laboratory at Colorado State University. Dr. Paustian received his M.S. in forest ecology from Colorado State University in 1980 and his Ph.D. in systems ecology and agroecology from the Swedish University of Agricultural Sciences in 1987. Dr. Paustian served as a coordinating lead author for the Intergovernmental Panel on Climate Change (IPCC) Greenhouse Gas Inventory Taskforce and has served on numerous other national and international committees involving climate and carbon cycle research. He has previously co-chaired a Task Force on "Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture" by the Council on Agricultural Science and Technology (CAST), and was lead author on a Pew Center report on "Agriculture's Role in Greenhouse Gas Mitigation." Dr. Paustian's research interests include soil organic matter dynamics, carbon and nitrogen cycling in cropland and grassland ecosystems, and the evaluation of environmental impacts of agricultural bioenergy production.

Jianwu (Jim) Tang, Marine Biological Laboratory

Dr. Jianwu (Jim) Tang is an associate scientist in The Ecosystems Center of the Marine Biological Laboratory in Woods Hole, Massachusetts. Dr. Tang received his Ph.D. in ecosystem sciences from the University of California, Berkeley, in 2003. Following his degree program, Dr. Tang was a research associate at the University of Minnesota focusing on forest carbon cycles. Dr. Tang is currently serving on the Steering Committee for the Global Science and Data Network for Coastal Blue Carbon, funded by the Carbon Cycle Interagency Working Group (CCIWG), and is a member of the American Geophysical Union and Ecological Society of America. Dr. Tang is currently researching greenhouse gas (CO_2, CH_4, and N_2O) emissions from agro-ecosystems and wetlands and their responses to management and disturbance. The wetland work evaluates the role of "blue carbon" in coastal wetlands and the significance of wetland restoration in carbon sequestration.

Tiffany Troxler, Florida International University

Dr. Tiffany Troxler is the director and associate director for Science of the Sea Level Solutions Center. The Center's work is to advance knowledge, decision making, and actions toward mitigating the causes and adapting to the effects of sea-level rise. She is also research associate professor in the Department of Biological Sciences at Florida International University in Miami, Florida. Some of her projects include collaborative research that examines the effects of saltwater inundation on Everglades coastal wetlands, assesses management actions associated with Everglades restoration, and advances interdisciplinary urban solutions to sea-level rise. She is also collaborating on the Florida Coastal Everglades Long-Term Ecological Research program. She is co-editor and contributing author on two IPCC methodological reports that guide national greenhouse gas inventories on managed wetlands. Dr. Troxler received her master's and Ph.D. in biological sciences from Florida International University in 2001 and 2005, respectively.

Michael Wara, Stanford University

Dr. Michael Wara is an associate professor of law at Stanford University. Dr. Wara received his J.D. from Stanford Law School and his Ph.D. in ocean sciences from University of California, Santa Cruz. An expert on energy and environmental law, Dr. Wara's research focuses on climate and electricity policy. His current scholarship lies at the intersection between environmental law, energy law, international relations, atmospheric science, and technology policy. Dr. Wara joined Stanford Law in 2007 as a research fellow in environmental law and as a lecturer in law. Previously, he was an associate in Holland & Knight's Government Practice Group, where his practice focused on climate change, land use, and environmental law. Dr. Wara is a research fellow at the Program in Energy and Sustainable Development in Stanford's Freeman Spogli Institute for International Studies, a faculty fellow at the Steyer-Taylor Center for Energy Policy and Finance, and a center fellow at the Woods Institute for the Environment.

Jennifer Wilcox, Worcester Polytechnic Institute

Dr. Jennifer Wilcox is the H. Manning Professor of Chemical Engineering at Worcester Polytechnic Institute. Dr. Wilcox earned a B.A. in mathematics from Wellesley College and a Ph.D. in chemical engineering from the University of Arizona. Dr. Wilcox received an Army Research Office (ARO) Young Investigator Award (Membrane Design for Optimal Hydrogen Separation), an American Chemical Society Petroleum Research Fund (ACS PRF) Young Investigator Award (Heterogeneous Kinetics of Mercury in Combustion Flue Gas), and a National Science Foundation CAREER Award (Arsenic and Selenium Speciation in Combustion Flue Gas). She has served on several committees, including for the National Academy of Sciences, Engineering, and Medicine and the American Physical Society, to assess CO_2 capture methods and impacts on climate. Along with her lab, Dr. Wilcox's research interests combine experimental and theoretical methods to investigate capture and sequestration of trace metals (mercury, arsenic, and selenium) and CO_2.

APPENDIX B

Disclosure of Conflict of Interest

The conflict-of-interest policy of the National Academies of Sciences, Engineering, and Medicine (www.nationalacademies.org/coi) prohibits the appointment of an individual to a committee like the one that authored this Consensus Study Report if the individual has a conflict of interest that is relevant to the task to be performed. An exception to this prohibition is permitted only if the National Academies determine that the conflict is unavoidable and the conflict is promptly and publicly disclosed.

When the committee that authored this report was established a determination of whether there was a conflict of interest was made for each committee member given the individual's circumstances and the task being undertaken by the committee. A determination that an individual has a conflict of interest is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

Dr. Christopher W. Jones was determined to have a conflict of interest because of his financial interests in Global Thermostat LLC.

The National Academies determined that the experience and expertise of the individual was needed for the committee to accomplish the task for which it was established. The National Academies could not find another available individual with the equivalent experience and expertise who did not have a conflict of interest. Therefore, the National Academies concluded that the conflict was unavoidable and publicly disclosed it through the National Academies Current Projects System (www8.nationalacademies.org/cp).

APPENDIX C

Coastal Blue Carbon: Macroalgae

Macroalgae, commonly known as seaweed, are fast-growing aquatic organisms. Macroalgae occur in its largest stands as kelp forests in temperate regions including U.S. coastlines. Unlike coastal wetland habitats, macroalgae are largely attached to rocky surfaces and do not accumulate carbon in soils with extensive root systems. An estimated 82 percent of kelp productivity becomes detritus (Krumhansl and Scheibling, 2012). Carbon sequestration can thus only occur if carbon is buried in sediments or exported into the deep ocean and sequestered long term. Most carbon from macroalgae is assumed to return to the carbon cycle through herbivory and thus extensive study on its carbon storage rate and capacity has not been conducted (Howard et al., 2017). Krause-Jensen and Duarte (2016) have synthesized data from studies of macroalgae transport and occurrence in the deep ocean to develop a rough estimate for macroalgae's carbon removal potential. They identified potential opportunities for carbon storage through burial within the algal beds, burial in the continental shelf, export to below the mixed ocean layer, and export to the deep sea. Using an approximate global net primary production (NPP) of 1,521 TgC/y, they estimate that macrolagae may be sequestering 173 TgC/y, or a removal rate of 11 percent per year. Most of this is assumed to be sequestered in the deep ocean.

Large uncertainties persist in evaluating macroalgae as a reliable coastal CO_2 removal approach because of unknowns in their global areal extent, the fraction of carbon that may be sequestered, and the timescale at which carbon storage may occur. Estimates based on ecosystem suitability modeling indicate that the maximum potential global area for macroalgae may be as high as 570 million ha (Gattuso et al, 2006). The ocean processes that affect algal transport and storage are not well understood and could provide more accurate assessment of natural carbon sequestration. Carbon storage may also be dependent on the species of macroalgae and its carbon content and lability (Trevathan-Tackett et al., 2015).

Restoration of kelp beds may increase the amount of carbon sequestered in the deep sea. However, there will also be increases in the kelp that floats onto beaches or is made available to the food web, the transport and impacts of which would need to be understood. Aquaculture activities may be more controlled; however, seaweed farming for sequestration would be in competition with its potential food and energy usages. Methods for seaweed aquaculture may increase carbon removal exponentially by floating seaweed beds near the surface (Duarte et al., 2017). However, these floating beds would not be subject to the same export processes, and natural sequestration from such beds is not clear. Seaweed culture is generally considered for use for food or energy rather than as a NET. The longevity of existing or restored kelp stands may be impacted by warming waters and ocean acidification, such as in a reduction in germination (Gaitán-Espitia et al., 2014), however the impacts are not always seen and may be species dependent and dependent (Leal et al., 2017; Olischläger et al., 2017; Xu et al., 2015). Warming waters may also lead to increased sea urchin grazing (Nabuurs et al., 2007). Kelp beds provide co-benefits of habitat for fish and invertebrate species, and attenuate wave energy for coastal protection (Narayan et al., 2016).

APPENDIX D

CO_2 Flux Calculation

The flux of carbon dioxide (CO_2) across an interface is an important parameter in determining the amount of material required for a given amount of separation in addition to the size of the contact area required. The flux of CO_2 across an interface may be represented by:

$$J_{CO_2} = C_i k_l E = \left(\frac{p_{CO_2}}{H}\right) k_l E$$

Such that,

JCO_2 = flux of CO_2 across the interface from gas to liquid in the case of a solvent or from gas to pore in the case of a solid sorbent

C_i = concentration of CO_2 at the interface. In the case of a solvent, this is the Henry's law solubility. In the case of a solid sorbent it could be the equilibrium capacity of the material based upon a Henry's law estimation approach.

H = Henry's law constant in units of atm·cm^3/mol

pCO_2 = partial pressure of CO_2

k_l = mass-transfer coefficient. In the case of a solvent, this is strictly the liquid-phase mass-transfer coefficient. In the case of a solid sorbent or mineral, this could be an effective mass-transfer coefficient, based upon all of the dominating diffusion resistances present in the system (see Ruthven, 1984 for details), that is, water on the pellet, macropore diffusion, etc.

E = enhancement factor, which is only present when a chemical reaction takes place

For simplicity, and to exhibit the unique requirements required of a CO_2 separation process for an extremely dilute system (air) compared to a moderately dilute system (coal exhaust), only solvent-based separation will be considered in the remainder of this discussion. The enhancement factor, E, can be calculated for a chemically-reacting solvent based upon the concentration of reactant present and the rate of chemical reaction. For instance, the reaction may take place instantaneously, which means CO_2 reacts at the interface, indicating that the base reacting with CO_2 is much greater in concentration than CO_2 present at the interface. In this case, $E = E_i$, such that

$$E_i = 1 + \frac{D_B c_B}{z D c_i}$$

where D_B equals the diffusivity of the base, c_B is the concentration of the base, z is the stoichiometric coefficient of the base in the chemical reaction, D is the CO_2 diffusivity, and c_i is the interfacial concentration of CO_2.

Most solvents to date do not react with CO_2 instantaneously, but rather via a fast pseudo-first-order reaction, in which case,

$$E = \sqrt{D k c_B}$$

such that k is the rate of the chemical reaction. In this case, the equation on page 469 can be rewritten as:

$$J_{CO_2} = \left(\frac{p_{CO_2}}{H}\right) k_l \sqrt{D k c_B}$$

which would represent the CO_2 flux across the gas-liquid interface of the majority of solvents known today.

Figure D.1 shows the interfacial concentration as a function of p_{CO_2} and H or air capture (top) and the flue gas of natural gas and coal-fired power plants (bottom). To illustrate the impact that dilution has on the CO_2 flux, taking amine-based solvents as an example, for air capture, c_i is ~10, while for coal-fired flue gas, it is approximately 250 times greater at approximately 2,500 mol/cm^3. Based upon the flux equation, this means that to enhance the flux of CO_2 across the gas-sorbent interface for the case of air capture, the product $k_L E$ must be 250. The mass transfer coefficient changes by at most a factor of 10. The mass-transfer coefficient, k_L, is dependent on the process parameters used in contacting the air and sorbent. For instance, the air can interact with the sorbent via coated packing or bubbles. In addition, the way in which the air flows over the solvent impacts this parameter, that is, cross-flow vs counter-flow. The enhancement factor depends primarily on the rate constant of the chemical reaction between CO_2 and the chemical binding to it. Hence, a chemical with a rate constant 25 times greater, combined with a process that allows for the mass-transfer coefficient to be maximized, has the potential to create a flux for air capture equivalent to the more concentrated scenario of coal-fired flue gas exhaust. It is not necessary for the air capture flux to match that of flue gas for its success, but improving materials in this way could results in more competitive costing because the capital expense would surely decrease with fewer required units for separation. Hence, the development of new chemistries that could lead to enhancing the rate of chemical reaction with CO_2 could

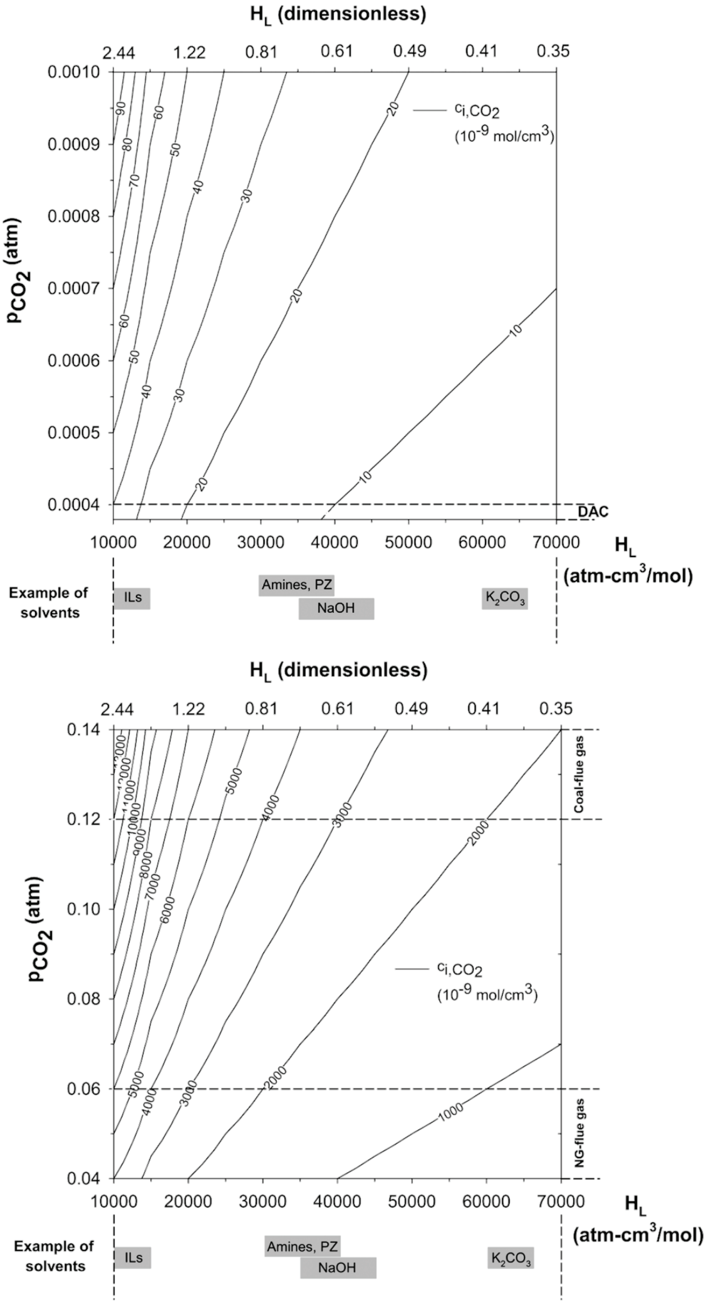

FIGURE D.1 Interfacial concentration of CO_2 as a function of CO_2 partial pressure between 0.0004-0.001 atm (top) and 0.04-0.14 atm (bottom) and Henry's law constant between 10,000-70 000 atm-cm3/mol, spanning that of ionic liquids to potassium carbonate. SOURCE: Wilcox et al., 2014.

be of interest in terms of future research. These new chemistries could also play a role in enhancing the flux of CO_2 for more concentrated CO_2 cases as well.

SOLID SORBENT SYSTEM

To assess the bounds of a generic, hypothetical air capture process employing adsorption as the separation technology, the methodology outlined in the work of Sinha et al. (2017) was employed. This approach, applying mass and energy balances to each individual step in the overall process, calculating energy requirements, and then assessing the costs of the necessary capital equipment, has been applied to various scenarios to arrive at overall costs for the separations process.

In the analysis employed, an array of critical parameters was defined within a range of values deemed physically realistic, and from these parameters other key parameters are calculated (Figure D.2). A stepwise approach to calculating process energetics and costs was then applied. In the first step, the contactor:adsorbent ratio, adsorbent purchase cost, and adsorbent lifetime are defined. The contactor is the structure that

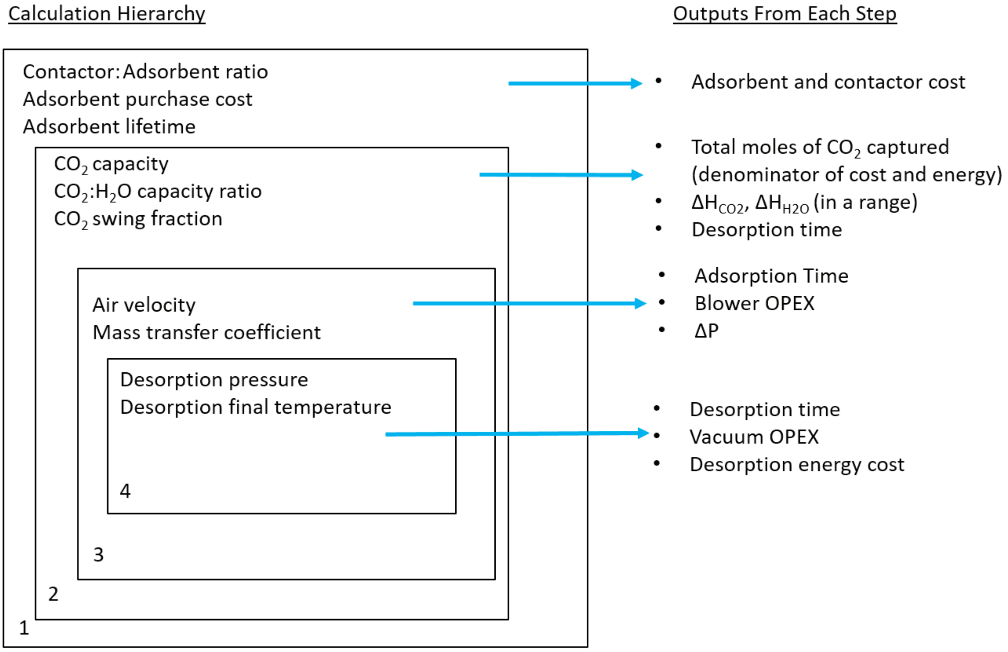

FIGURE D.2 Approach to calculating energy costs and process economics for a generic adsorption-based air capture process.

provides for high surface area gas-solid contacting, whereas the adsorbent is the chemical agent that binds the CO_2. From these values, the adsorbent and contactor costs are determined. In the limiting case where the adsorbent and contactor are the same, the contactor cost goes to zero. This case was not specifically considered here.

Next, the total CO_2 capacity was defined, the ratio of the CO_2 and H_2O capacities, and the fraction of captured CO_2 desorbed and collected as product (CO_2 swing capacity) were defined. These define the total moles of CO_2 captured, which is a key parameter in the denominator of the cost and energy. The heat of adsorption of CO_2 is also defined, constrained within a range (ΔHCO_2). The desorption time is also defined based on a transient energy balance calculation using 100°C saturated steam as the heat transfer media, which transfers heat through the heat of condensation. In these calculations, the model envisaged that the steam is directly contacted with the sorbent, providing both a concentration and thermal driving force for desorption. In this approach, the sorbent quickly attains a pseudo-steady-state capacity of adsorbed water, becoming hydrated after steaming, with some water desorption occurring via evaporative cooling upon exposure to fans blowing air through the material in the next adsorption step. Based on the water transfer rate, the amount of water lost by evaporation was calculated such that the heat transfer was sufficient to reduce the sorbent/contactor combination to the initial conditions based on the sensible heat requirement of the adsorbent/contactor system (Jeong et al., 2010). This is essential to re-initialize the system for the next adsorption step. Given the high content of adsorbed water on the sorbent surface owing to the direct steaming heat transfer approach, the amount of water adsorbed from the air in each adsorption cycle is estimated to be minimal in this gas-solid contacting strategy. In contrast, alternate strategies are being employed in practice, whereby heat is transferred indirectly and the steam does not directly contact the sorbent. This alternate approach might offer less efficient heat transfer but better protects the sorbent from possible degradation by direct steam contact. This approach also would result in more water being extracted from humidity in the air. No attempt was made to model every known process, but rather to use the representative, generic process for energy and cost estimations.

In the next phase, the pressure drop is derived from a calculation that considers the velocity, contactor length, and radius of a contactor channel. The mass-transfer coefficient is derived from the velocity calculation. The mass-transfer coefficient is a lumped parameter that accounts for all potential resistances to mass transfer, including film resistance, macropore resistances, as well as micropore resistances. The adsorption time depends on the mass transfer coefficient, pressure drop, and velocity. From these parameters, blower or fan operating costs were determined.

TABLE D.1 Parameters Used to Calculate Lower-Bound and Upper-Bound Costs for Direct Air Capture with Solid Sorbents

Process Parameters	**Lower/Upper Bounds**
Adsorbent purchase cost ($/kg)	15/100
Adsorbent lifetime (yrs)	5/0.25
Sorbent total capacity (mol/kg)	1.5/0.5
Desorption swing capacity	0.9/0.75 SCmax
CO_2:water ratio	1:2/1:40
Desorption pressure (bar)	0.2/1
Final desorption temperature (K)	340/373
Thermal Energy Outputs	
MJ/mole	0.08/0.85
GJ/tCO_2	1.85/19.3
kW-hr/tCO_2	514/5367
Electrical Energy Outputs	
MJ/mole	0.003/0.167
GJ/tCO_2	0.08/3.79
kW-hr/tCO_2	20/1055
Cost	
$/t$CO_2$	14/1065

NOTE: Energy expenditure associated with upper- and lower bound-process configurations.

In the last step, the desorption pressure was varied within a range and the final desorption temperature of the contactor/adsorbent material was similarly defined. By conducting a transient heat transfer calculation using 100°C saturated steam as the heat transfer media, as noted above, with a final desorption temperature defined, the desorption time was calculated. Other outputs from this step include the vacuum operating costs as well as the desorption energy costs (steam costs).

The calculation procedure and outputs from each step is schematically shown in Figure D.2. The range of parameter variation is given in Table D.1.

The conditions leading to the lower- and upper-bound costs are outlined here. As noted above, the combination of all the most favorable parameters, using realistic physical parameters, suggests that a hypothetical cost as low as \$18/tCO_2 can be estimated. The upper-bound cost (\$1,060/tCO_2) is not a true upper bound, because there are an infinite number of ways to deploy direct air capture with high costs. The term upper bound solely signifies the upper end of the range considered in the calculations. The committee does not feel that the lower bound cost is practically achievable, though no physical bounds prevent the cost of direct air capture from dropping below \$100/tCO_2.

RENEWABLE ROUTES WITH SOLVENT-BASED SYSTEMS

Costing Air Capture from Renewables—achieving 1Mt CO_2 avoided per year

Two routes to costing air capture using 100 percent renewables were considered: (1) electricity sourced from combined photovoltaics (PV) and battery storage for direct use and (2) electricity sourced from PV for electrolysis (Figure D.3; Table D.2), followed by H_2 storage as described in detail in Chapter 5. In these low-carbon scenarios, solar thermal and geothermal were not considered because of their temperature limitations and inability to reach the required calcination temperature of 900°C. It should be noted however that technologies are emerging, such as concentrated power towers (DOE, 2013) and alternative nuclear designs (Harvey, 2017), that involve high-temperature gas-cooled reactors that may be suitable low-carbon routes for integration into air capture approaches requiring high temperatures for regeneration.

SECOND-LAW EFFICIENCY CALCULATION

The second law efficiency calculation for the separation of CO_2 from the atmosphere for a process employing a solid sorbent, as described above, is given here.

$$\eta = \frac{W_{\min}}{W_{DAC}}$$

$$where,$$

$$W_{DAC} = \sum_{in} W + Q_{in}\left[1 - \frac{T_0}{T_{utility}}\right] - \sum_{out} W - Q_{out}\left[1 - \frac{T_0}{T_{utility}}\right]$$

$$W_{\min} = \text{Minimum theoretical energy required for unmixing of two ideal gases}$$

This estimate demonstrates that an air capture process using solid sorbents and operating near ambient conditions, using low temperature thermal energy, can be surprisingly efficient. Despite the high dilution of the source gas, a process suitably designed

TABLE D.2 Economic Costs Associated PV + Storage for Solvent-Based Air Capture

CAPEX	Cost ($M)	Comment
Contactor array	150-250	*Lower bound*: anticipated cost of 10 air contactor array from Holmes and Keith (2012), based on optimal percent capture of 75% and bed depth of 6-8 m. *Upper bound*: scaled cost for system at high percentage capture (90%+) and deeper packing bed, with 1.5× learning cost factor.
Slaker/causticizer/ clarificator	130-195	*Lower bound:* capital costs taken from Socolow et al. (2011) report and adjusted to 2016 USD. *Upper bound*: 1.5× factor to account for new technology. Though the Ca-recovery cycle is mature and well studied in the pulp and paper industry, learning costs may be associated with integration into a direct air capture system.
Electric-fired calciner	270	Lower bound: price quote from industry source for oxy-fired kiln with 4.5× factor used for scaling Inside Battery Limits (ISBL) equipment costs to full costs. Assuming the lower-bound estimate because this may be lower than an oxycombustion or H_2-fired kiln since electric-fired kiln are commercially available. Efficiency of 80% assumed.

TABLE D.2 Continued

CAPEX	Cost ($M)	Comment
CAPEX Subtotal	*550-715*	
Annualized Capital Payment ($M/y)	62-80	Assumes a plant life of 30 years and fixed charge factor of 0.11278 (Rubin et al., 2007).

OPEX	Cost ($M/y)	Comment
Maintenance	23-40	Range calculated as 0.03 of total capital requirement.
Labor	7-12	Range calculated as 0.30 of maintenance cost.
Makeup (H_2O, KOH, $Ca(OH)_2$) and waste removal	5-7	*Lower bound*: assumes \$500/t KOH, \$250/t $Ca(OH)_2$, \$0.30/ t H_2O, \$260/t waste disposal (Rubin et al., 2007). *Upper bound*: applies 1.5 factor to make-up OPEX.
PV+battery	294-389	Levelized cost of energy "PV Plus Storage" \$92/MWh (Lazard, 2016). Assumes total capital costs of ~ \$3,900/kW including PV and battery energy storage. Assuming direct electricity needs of 21-27 kJ/molCO_2. Assuming electric kiln and electric heater have efficiencies of 80%, requires an electricity demand to meet thermal energy demands of 485-643 kJ/molCO_2.
OPEX Subtotal	*329-448*	

Cost = Net Removed CO_2 Cost (\$/tCO_2 yr^{-1})[a]	
PV+Battery	391-528

[a] Basis = 1Mt CO_2

and optimized to target ambient CO_2 can achieve the separation with unexpected efficiency. See Chapter 5 for calculated efficiencies.

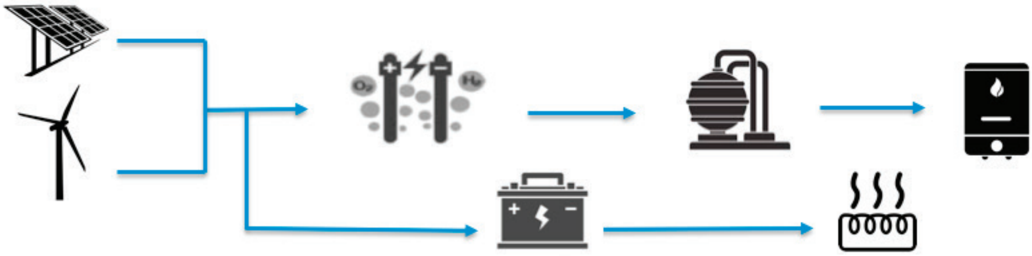

FIGURE D.3 Consideration of two routes to meeting the thermal needs of air capture, (1) electrolysis of H2, which is stored and used for H2-fired kiln (top) or (2) battery storage of renewable electrons for direct electric heating of an electric-fired kiln.

APPENDIX E

Carbon Mineralization

ENERGY BUDGET FOR "GENERIC" *EX SITU* MINERAL CARBONATION

This section focuses on energy use in a general general ex situ mineral carbonation process, where the energetic and material inputs and outputs will be examined for the following steps: extraction, reactant transport, pre-processing, chemical conversion, post-processing, product transport, and disposal or reuse. Because there are a variety of alkalinity sources (rocks and industrial waste products) and a number of possible reaction conditions (e.g., elevated temperature and pressure), all calculations are presented first generally and then applied to a case involving olivine carbonation at 155 and 100 bar.[1] A general scheme for this process is provided in Figure E.1.

Extraction, Reactant Transport, and Pre-Processing

Alkalinity stored in naturally occurring silicate deposits can be made available for onsite carbonation through mining, separating, crushing to size, and delivery via truck or rail depending on distance to source.[2] Because the drilling, blasting, excavation, and hauling activities associated with mineral extraction vary based on quarry location, the energetic consumption is expected to fall between similar low- and high-intensity extractions (97.0 MJ/t and 360.9 MJ/t) (Kirchofer et al., 2012). Based on electricity sourced from coal and natural gas, this results emissions of 0.02-0.08 t CO_2/t CO_2 processed and 0.013-0.05 t CO_2/t CO_2 processed, respectively.[3]

An additional source of alkalinity exists in the form of industrial waste by-products (e.g., cement kiln dust (CKD), steel slag, and coal fly ash (FA). Carbonation of these

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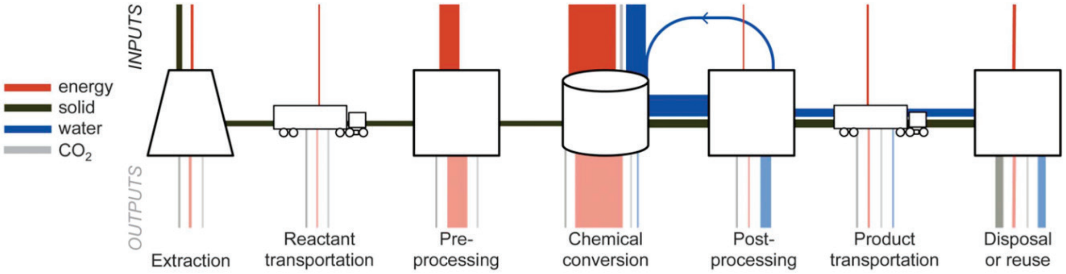
[1] This is in keeping with the development of ex situ mineral carbonation, which started with a single step, high-temperature, high-P(CO_2) reaction in an aqueous medium with naturally occurring minerals. (contacting CO_2 with dry rock was quickly shown not to work). Such processes were envisioned to use pure CO_2 gas. More recently, multistage extraction processes have been put forward. Some produce $Mg(OH)_2$ which can be reacted at lower (and possibly atmospheric) P(CO_2). The distinction is important. If direct single step mineral carbonation is used then a gas purification step is needed. If a multistage extraction process is used, then it may be possible to avoid pre-gas purification.

[2] It is assumed that rail transport is required for hauls more than 60 miles (one-way).

[3] Assumes a material loss of 1 percent.



	Extraction	Reactant transportation	Pre-processing	Chemical conversion	Post-processing	Product transportation	Disposal or reuse
Inputs							
Energy (GJ)	188	52	846	3,185	8	150	223
Solid material (t)	1,944	1,924	1,866	1,848	2,819	2,791	2,707
Water (t)	0	0	0	6,659	7,317	2,791	2,707
Recycled water (t)	0	0	0	731	0	0	0
Carbon dioxide (t)	0	0	0	1,000	0	0	0
Outputs							
Solid material (t)	1,924	1,866	1,848	2,819	2,791	2,707	2,707
Water (t)	0	0	0	7,317	2,791	2,707	2,707
Water for recycle (t)	0	0	0	0	731	0	0
Waste material (t)	19	58	19	102	3,822	168	0
Waste energy (GJ)	188	52	846	3,185	8	150	223
CO_2 emissions (t)	11	3	62	166	1	10	13

FIGURE E.1 Material and energy flows for an *ex situ* mineral carbonation process based on a carbonation rate of 1000 tCO_2 /day using and an olivine feedstock at 155 and 100 bar.
SOURCE: Kirchofer et al., 2012.

waste-products represents an opportunity for reliable carbon storage while also treating industrial waste that would otherwise require disposal. Additionally, waste from industrial manufacturing may fill niche scenarios whereby transport of crushed olivine or serpentine proves cost-prohibitive due to distance considerations. The energy required in handling and collecting of industrial alkalinity can be approximated as 50 percent of that outlined for the natural mineral extraction case above (Kirchofer et al., 2012).

Transport can be considered invariant to source and is reported as the energy required to move 1 ton of reactant material over 1 mile. Using a standard diesel conversion of 2.68 kg CO_2 per liter and assuming a 3 percent material loss during transport, transport via truck and rail freight yields 0.11 kg CO_2 and 0.03 kg CO_2 per ton-mile, respectively. Alternatively, in some cases *ex situ* mineral carbonation could be done at the source of solid reactants (mine tailings, quarry, alkaline waste site) with very low transport costs (Moosdorf et al., 2014), for example by building direct air capture plants at the source.

In the final step before chemical conversion, the feedstock must be ground to reduce the input particle size (*ca.* 10,000 microns) to an output size suitable for efficient conversion (4 to 2000 microns). The electric work for grinding is a function of the

80 percent passing size of the feedstock grain size (*I)* and desired grain size (*O*), in microns:

$$W_g = 10W_i\left(\frac{1}{\sqrt{O}} - \frac{1}{\sqrt{I}}\right)$$

where W_i is the Bond's work index[4] for the material (Gupta et al., 2006). Using the olivine work index value, this corresponds to 2.0 and 1.0 $kgCO_2$/t using electricity sourced from coal and natural gas fired plants, respectively.

Chemical Conversion

In the conversion of carbon dioxide, alkalinity must be liberated via dissolution of the pre-processed feedstock, followed by heating and mixing of the reactants to precipitate the stable carbonate. Water consumption during this process is estimated as 6.7 tH_2O / tCO_2 processed (Kirchofer et al., 2012) less 0.73 tH_2O/tCO_2 processed recycled from downstream processing, yielding a net water consumption of 5.9 tH_2O/tCO_2 processed. Energy consumption to deliver and recycle water for chemical conversion is estimated at 4.66 MJ/tCO_2 processed, resulting in 1.0 and 0.6 $kgCO_2/tCO_2$ processed using power sourced from coal and natural gas, respectively.

The energy required to mix reactants is determined from the mixing power, P_m:

$$P_m = N_p \rho N^3 D^5$$

where N_p is the power number (3.75 in this case), ρ is the mixture density, *N* represents the impeller speed (0.6 rps), and *D* represents the impeller diameter, taken as one-third of the reactor tank diameter.[5] The total energy is thus contingent on the reaction speed, where the rate of CO_2 carbonation is considered limiting. Here it is assumed that the rate of carbonation is dependent on the alkaline feedstock dissolution and not on the mass transfer of CO_2 into the liquid phase.

Heat input is required to bring the reactants (including water) up to reaction temperature plus any additional energy to compensate for heat loss from the reactor vessels. The former is calculated from the specific heat capacity and temperature change required:

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[4] W_i = 12.00, 13.49, 13.39, 11.31, and 11.61 kWh per tonne for SS, CKD, FA, olivine and serpentine, respectively.

[5] Two reactor tanks are considered: (1) for ambient pressure conversion (10 m diameter, 785 m^3 volume) and (2) for high-pressure conversion (up to 100 bar, 2 m diameter, 27 m^3 volume).

$$q = mC_p\Delta T$$

However, this heating requirement is effectively lowered because relevant reactions are exothermic.[6] Heat loss is calculated assuming that the heat flux (ϕ_q) from the stainless-steel tank is equal to heat flux to the surroundings, and is calculated from:

$$\phi_q = h(T_o - T_a) + \varepsilon_1\sigma(T_o^4 - T_a^4)$$

where h represents the convection coefficient (20 W m^{-2} K^{-1} in this case), ε_1 is the emissivity for the tank insulation material (0.050 for mineral fiber), σ is the Stefan-Boltzman constant, and T_o and T_a represent the temperature of the outer tank surface and the ambient surroundings, respectively.

Considering water demand, mixing of reactants, and reaction temperature maintenance, the total energy required for chemical conversion of olivine at 155 is 3.185 GJ/tCO_2 processed, or 0.70 tCO_2 and 0.43 tCO_2 of additional emissions based on power from coal and natural gas, respectively.

Post-Processing, Product Transport, and Reuse or Disposal

After conversion, the solid carbonate product must be clarified to remove and recover water, then separated via liquid cyclone, centrifugal filtration, or a combination in series. Following separation, the product is transported for reuse as an aggregate material or disposed of as mine back-fill.

In post-processing, a material loss of 5 percent is assumed. Energy requirements are calculated assuming a processing train of clarification, liquid cyclone separation, and centrifugal filtration. In the first step, 75-80 vol.% water is clarified from the product mixture of 0.1-35 wt% solids. Clarification power is calculated from:

$$P_{cl} = c_{cl}D^2$$

where the coefficient c_{cl} is taken as 0.0045 and the tank clarifier tank diameter D is taken as 25 m,[7] and the volumetric flow rate is assumed to be 0.20 m^3/s.

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[6] The standard heat of reaction for carbonation is –179 kJ/mol for industrially-sourced alkalinity, –88 kJ/mol for olivine, and –35 kJ/mol for serpentine.

[7] Typical values for c_{cl} range from 0.003 to 0.006, with typical clarifier tank diameters from 2–200 m.

After clarification, the product mixture is fed to the liquid cyclone process to produce a 30-50 wt% solid mixture. The power requirement for this step is a function of the volumetric flow rate q_v:

$$P_{lc} = c_{cl} q_v$$

where the coefficient c_{lc} is taken as 200[8] and is 0.075 m^3/s. This mixture is passed for additional processing in the centrifugal filter to produce an 80-95 wt% solid mixture. The power requirement in this step is a function of the solids input rate, q_m (kg/s):

$$P_{cf} = c_{cf} q_m$$

where the coefficient c_{cf} is taken as 16.5 and the volumetric flow rate is 0.076 m^3/s. The collective power requirement for post-processing is 8 MJ / tCO_2 carbonated, which results in a negligibly small carbon footprint in comparison to other steps in the carbonation chain.

Product transport is similar to reactant transport and energy requirements are calculated using the same fuel economies presented in the reactant transport section. However, the total product weight is greater than the total reactant weight per tCO_2 carbonated (ca. 44% more weight in the case of olivine carbonation); thus, the levelized emissions from product transport are expected to be greater than those reported for reactant transport.

If the processed material is reused, it is necessary to quantify the emissions saved in the displacement of an aggregate product. Here, the life cycle energy associated with medium-intensity mining and extraction of crushed limestone serves as a general representation of the energy saved in reuse of carbonate as an aggregate material (Kirchofer et al., 2012). This equates to an energy credit of 97 MJ/t, or 21 and 13 $kgCO_2$ for coal and natural gas, respectively. If, instead, the processed carbonate heads for open mine disposal as back-fill, the energy cost can be assumed as 50 percent that of low-intensity mining.

The total cost for an ex situ mineral carbonation system is an order of magnitude larger than that observed for in situ systems (Table E.1). A previous National Academies of Sciences, Engineering, and Medicine (NASEM) study examined the cost of mineral carbonation based on the exampled presented in Kirchofer et al., 2012 and obtained a similar result of \$1,000 /t CO_2 reliably stored (NASEM, 2015). The dominant capital factor involves the reactor vessels that house the chemical conversion of CO_2 into stable mineral form, while the dominant operating cost involves delivery of

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[8] Typical values for c_{lc} range from 100 to 300; values for c_{cf} range from 3-30, while values for q_v range from 0.002 – 0.015 kg/s.

alkalinity to the facility. This latter cost can be mitigated if the ex situ facility is positioned to take advantage of local alkalinity resources. Though a thorough life cycle analysis on treatment of industrial waste products has shown that these processes are far more carbon intensive than those involving the mining, transport, and grinding of natural silicate minerals (i.e., 200-500 tonnes less avoided per 1000 tonnes CO_2 reliably stored), these processes may garner more public support by virtue of waste treatment (Kirchofer et al., 2012).

TABLE E.1 Economic Costs Associated with Reliable Storage via Ex Situ Mineral Carbonation

CAPEX	**Cost ($M)**	**Comment**
Grinding	44	Estimate scaled from Huijgen et al. (2007) assuming two grinders operated in succession: (1) cone crusher and (2) ball mill to achieve particle size of ca. 10 microns.
Reactor vessels	2,700	Estimate scaled from Huijgen et al. (2007) assuming type *a* reactor tank (see Kirchofer et al., 2012), 780 m^3 capacity, and ~150 tanks required to process volume of material necessary to reliably store 2,778 tCO_2/d.
Filtration system	30	Estimate scaled from Huijgen et al. (2007) assuming rotating vacuum tumble filter with 50 m^2 filter area collects 8.8 m^3 filtrate/day.
CAPEX Subtotal	2,774	
Annualized Capital Payment ($M/y)	*313*	Assumes a plant life of 30 years and fixed charge factor of 0.11278 (Rubin et al., 2007).
OPEX	**Cost ($M/y)**	**Comment**
Maintenance	83	Range calculated as 0.03 of total capital requirement.
Labor	25	Range calculated as 0.30 of maintenance cost.

TABLE E.1 Continued

Total fuel (coal, natural gas, electricity)	140	Collective energy cost for all steps including mining, pre- and post-processing, chemical conversion, transport, and disposal. Excludes energy costs associated with capture, compression, and transport of CO_2. Excludes petroleum cost for alkalinity transport, which is assumed into the delivery cost. Assumes \$3/GJ for natural gas, Appalachian medium-sulfur coal, cost of \$50/t, and higher heating value (HHV) of 31 GJ/t (Rubin et al., 2007), and \$60 MWh electric cost.
Alkalinity delivery	250	Assumes alkalinity delivery cost of \$250/tCO_2 fixated. Cost reflects mining and transport via trucking. Rail costing may be cheaper for greater distances (>100 km) or where the mineral carbonation site exists at a railhead.
Capture, compression, and delivery of pure CO_2	40-70	Reflects cost of capture, compression and transport via pipeline (assumes 250 km) (Rubin et al., 2015). Range exists for various point sources (e.g., supercritical pulversized coal (SCPC) vs natural gas combined cycle (NGCC), average value of 55 used in total.
OPEX Subtotal	*553*	
Levelized Cost (\$/tCO_2 yr^{-1})[a]	**866**	
Avoided Cost (\$/tCO_2 yr^{-1})[b]	**1170**	

[a] Levelized basis = 1Mt CO_2.

[b] Levelized basis = 0.74 Mt CO_2 (Kirchofer et al., 2012).

APPENDIX F

Geologic Storage

ENERGY REQUIREMENTS AND COSTS FOR COMPRESSION, TRANSPORT, AND INJECTION OF CO_2

This appendix calculates the energy requirements and costs for compressing captured carbon dioxide (CO_2), transporting it to the sequestration site, and injecting it into a deep sedimentary formation. It also provides the timeline and costs for an experimental injection of CO_2 into peridotite or basalt (Table F.3).

COMPRESSION AT THE CAPTURE UNIT

Following separation of CO_2 from flue gas, air, or some other source, the now rich CO_2 stream must be dehydrated and compressed to a level suitable for transport, typically above 10 MPa for pipeline to ensure that the supercritical phase is maintained and frictional losses overcome. Compression power is calculated from:

$$W_c = \frac{ZRT_1}{M}\frac{N\gamma}{\gamma - 1}\left[\left(\frac{p_2}{p_1}\right)^{\gamma-1/N\gamma} - 1\right]$$

where Z is the compressibility factor (0.9942), T_1 is the inlet temperature (313.15 K), R is the universal ideal gas constant (8.3145 J/(mol K), M is the molar mass of CO_2 (44.01 g/mol), N is the number of compression stages (4), γ is the specific heat ratio (1.293759), and p_1 and p_2 are the inlet and outlet pressures, respectively (0.101325 and 11 MPa) (Damen et al., 2007). Based on these parameters, and assuming an isoentropic efficiency of 80 percent, the electrical work for compression equals 400 MJ/t CO_2, or 0.09 and 0.055 t CO_2 emitted per t CO_2 compressed using electricity sourced from coal and natural gas, respectively. Material requirements for the construction and demolition of compression equipment and infrastructure are negligibly small and can be ignored in this analysis.

PIPELINE TRANSPORT

There are three factors to consider in estimating the carbon footprint of a CO_2 pipeline: (1) the embodied energy in the materials used in construction (including transport of these materials to the building site and demolition at end-of-life), (2) indirect emissions associated with the electricity required to power CO_2 pumps along the pipeline length to maintain pressure, and (3) fugitive emissions associated with leakage and loss of CO_2 over the pipeline lifetime. All calculations assume a 10-mile pipeline length and all associated components are expected to scale linearly for longer pipelines.[1] The dimensions used in these calculations are sufficient to transport 10 Mt/y CO_2.

Materials, Construction, and Demolition. The major material requirements for pipeline construction include 31,200 t sand and 7,680 t steel (Koornneef et al., 2008). The embodied energy in steel is 11,254 MJ/t (Kirchofer et al., 2012), such that every 10-mile section of pipeline results in emissions of 0.02 and 0.012 Mt CO_2 from the production of steel,[2] using energy sourced from coal and natural gas, respectively. Collection and handling of sand is expected to have a small energy requirement relative to transport and is thus ignored. Transport of all materials to the construction site results in 2.26×10^6 ton-miles of material hauling. Assuming an energy density of 35.9 MJ/L for lower heating value (LHV) diesel with a carbon intensity of 102.82 g/MJ, this material can be transported via heavy-duty trucking at an emission rate of 0.11 $kgCO_2$ per ton-mile, or 249 tCO_2 per 10-mile pipeline segment. Energy consumed over the course of construction is estimated at 53,000 GJ diesel per 10-mile segment (Koornneef et al., 2008). Using the same energy density and carbon intensity described above yields an additional 5.4 kt of CO_2 emissions.

After a pipeline lifetime of 30 years, all materials must be demolished and transported off-site. Here, it is assumed that 50 percent of the materials are left in-ground and 50 percent are demolished and hauled away (Koornneef et al., 2008). Assuming a demolition energy of 11.1 MJ/t (Phua, 2009), and a hauling requirement equal to 50 percent of that required for construction, an additional 0.15 $ktCO_2$ is emitted in pipeline removal.

Pipeline Compression. The optimal number of pumps to overcome pressure loss[3] along the pipeline length is calculated from the DOE Fossil Energy (FE)/ National

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[1] For example, if a 10-mile segment requires 80,000 t steel, a 50-mile segment requires 400,000 t.

[2] Analysis assumes primary steel. Adjustments for secondary steel may assume an embodied energy of 7,230 MJ/t.

[3] Assuming an 11 MPa input pressure and 10.7 MPa output pressure.

Energy Technology Laboratory (NETL) CO_2 Transport Model (NETL, 2018). For the case of a 10-mile pipeline segment with nominal diameter of 30 inches, two compression pumps (η= 0.75) are spaced 3.3 miles apart and require 8,379 MWh/y—collectively—to operate. This compression work adds 6.6 and 4.1 ktCO_2 per year, or 198 and 123 ktCO_2 over the lifetime of the pipeline, using energy sourced from coal and natural gas, respectively. The number of compression pumps does not scale perfectly linearly as the materials, and a pipeline model (e.g., FE/NETL model) should be used to assess the optimal number of pumps for a given length and desired pressure.

Fugitive Emissions. Over the course of compression and transport, a small percentage of CO_2 will be lost due to system leakage. Using guidelines for fugitive emission calculations provided by the IPCC (2006), an estimated 3.74 tCO_2/mile per year is lost, or 1.12 ktCO_2 per 10-mile segment over the course of the pipeline lifetime.

INJECTION

This section outlines the carbon footprint of CO_2 injection with the ultimate goal of permanent storage in the subsurface.[4] This chain involves construction of the injection well plus compression and injection energy to pump approximately 7.3 Mt/y underground.[5] Emissions associated with materials (embodied energy) and transport to the construction site are approached with the same assumptions outlined in "Pipeline Transport: Materials, Construction and Demolition" above. A key difference in the life-cycle treatment of injection wells is that after a 30-year lifespan, the injection well is abandoned; thus, no emissions are accountable to project demolition and disposal.

Materials and Construction. A 7.3 Mt/y injection project requires approximately 6 wells, each 1.86 miles in length. A smaller (larger) capacity can be achieved by subtraction (addition) of wells, and the calculations outlined in this section should be scaled accordingly. The material requirements for well construction include 712,000 t sand, 11,900 t steel, and 25,111 t concrete, resulting in 46,452,000 ton-miles of material hauling. Using an average value of 3,255 MJ/t for the embodied energy of reinforced concrete, indirect emissions from material production total 0.047 and 0.03 Mt CO_2 assuming power sourced from coal and natural gas, respectively. Transport of construction materials to the site results in an additional 5.11 ktCO_2 emissions. Energy consumed over the course of construction is unknown, but a conservative estimate may

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[4] Alternative injection goals (e.g., enhanced oil recovery) may require additional equipment and energy requirements for processing of re-circulated CO_2.

[5] This injection capacity is based on reports for underground natural gas storage, where the life-cycle data scales to a 7.3 Mt/y capacity operation.

be obtained from the energy of construction per ton of steel in the pipeline case. This results in a consumed energy of 255,400 GJ, or 37.3 ktCO_2 emissions.

***Injection Energy*.** Assuming a 0.3 MPa pressure loss over the course of pipeline transport, the CO_2 arrives at the wellhead at a pressure of 10.7 MPa. The energy required to pressurize the incoming CO_2 to 15 MPa for injection can be calculated from the same equation presented above for compression work post-capture. However, the pre-injection compression train requires only 2 stages to achieve the desired pressure of 15 MPa. Using the assumptions outlined in "Compression at the Capture Unit" above, and changing the inlet and outlet pressures to 10.7 and 15 MPa, respectively, the injection well compression energy totals 25.2 MJ/t, or 0.04 and 0.025 Mt CO_2 in indirect emissions if using power generated in coal and natural gas firing, respectively.

CARBON EMISSIONS AND COSTS

A summary of the carbon emissions and costs associated with compression, transport, and injection chain is presented in Tables F.1 and F.2.

TABLE F.1 Contributions to the Carbon Footprint from Compression, Transport, and Injection (kgCO_2emitted/tCO_2 processed[a])

	Power Source			
Parameter	**Diesel**	**Coal**	**Natural Gas**	**N/A**
Compression (at the capture unit)		90	55	
Embodied energy of materials (pipeline construction)[b]		0.2	0.13	
Transport of materials (pipeline construction)[b]	0.003			
Energy consumed in construction (pipeline)[b]	0.06			
Pipeline demolition	0.002			
Pipeline pumps		0.07	0.04	
Fugitive emissions				0.012
Embodied energy of materials (well construction)		0.2	0.14	
Transport of materials (well construction)	0.02			
Energy consumed in construction (injection well)	0.17			
Injection (compression) energy		0.18	0.11	
Total carbon footprint		90.9	55.7	

[a] Assumes a 30-year lifetime.

[b] Assumes a 10-mile segment.

TABLE F.2 Economic Costs Associated with Compression, Transport, and Injection of CO_2

Factor	Cost ($M)	Comment
CAPEX		
Compressor	100	Value scaled from integrated environmental control model (IECM) estimate, assuming a product pressure of 11 MPa, compressor efficiency of 80%, product purity of 99.5%, and a maximum CO_2 compressor capacity of 300 t/hr.
Pipeline	25–225	*Lower bound*: value calculated from the FE/NETL CO_2 Transport Cost Model.[a] Assumes 10 Mt/y transport and pipeline length of 10 mi. *Upper bound*: value calculated as above assuming pipeline length of 100 mi.
Injection site screening and evaluation	2.5	Value adjusted for current USD from estimate based on the work of Smith et al. (2001)
Injection equipment	0.6-8.0	Values calculated from actual injection site costs provided in Herzog et al., 2003) and include supply wells, plants, distribution lines, headers, and electrical services. Values called to current dollars. *Lower bound*: low case, aquifer[b] *Upper bound*: high case, gas reservoir[b]
Well drilling	0.20-210.0	Values calculated based on estimates provided in Herzog et al., 2003), which were derived from data presented in the report "1998 Joint American Survey (JAS) on Drilling Costs." Capital expense tied to number of wells required, which is in turn calculated from the equations outlined in McCollum and Ogden (2006) and uses the high- and low-case parameters outlined in the table notes[b] *Lower bound*: low case, aquifer[b] *Upper bound*: high case, gas reservoir[b]
CAPEX Subtotal	*128-546*	
Annualized Capital Payment ($M/y)	*14-62*	Assumes a project life of 30 years and fixed charge factor of 0.11278 (Rubin et al., 2007).

TABLE F.2 Continued

Factor	Cost ($M)	Comment
OPEX		
Maintenance: compression	3	Range calculated as 0.03 of total capital requirement for compression.
Labor: compression	0.9	Range calculated as 0.30 of maintenance cost for compression.
Electricity: compression	67-100	Calculated from energy requirement (400 MJ/t CO_2) and electricity cost range of $60/MWh lower bound to $90/MWh upper bound.
Operation and maintenance: pipeline	0.2-1.3	Pipeline operational and maintenance expenses reported in the FE/NETL CO_2 Transport Cost Model[a] includes labor, excludes cost of electricity. Range in costs reflect 10-mile (low) and 100-mile (high) pipeline segments.
Electricity: pipeline	0.2-2.9	Range calculated based on low case of 10-mile segment, 2,700 MWh/y electric requirement, and $60/MWh, and high case of 100-mile segment, 32,000 MWh/y electric requirement, $90/MWh.
Operation and maintenance: injection	0.6-34.0	Operational and maintenance costs estimated from McCollum and Ogden, 2006) and include: normal daily expenses, consumables, surface maintenance and subsurface maintenance. Compression energy at the wellhead is included and is considered negligible compared to other electric requirements in the transport and storage chain, thus no range for electric cost is reported. *Lower bound*: low case, aquifer[b] *Upper bound*: high case, gas reservoir[b]

continued

TABLE F.2 Continued

Factor	Cost ($M)	Comment
OPEX Subtotal	72-142	
Total Annual Cost	**86-204**	
Levelized Cost (\$/tCO$_2$ yr^{-1})[c]	**8.6-20.4**	
Avoided Cost (\$/tCO$_2$ yr^{-1})[d]		
Natural Gas	**9.1-21.6**	
Coal	**9.5-22.4**	

[a] See https://www.netl.doe.gov/projects/energy-analysis-details.aspx?id=543 (accessed January 29, 2019).

[b] High and low cases were calculated for three injection sites: aquifer, oil reservoir and gas reservoir. Variables for each scenario include reservoir pressure, thickness, depth, and horizontal permeability. These values are taken from Herzog et al., 2003) and are tabulated in McCollum and Ogden, 2006).

[c] Levelized basis = 10 Mt/y CO$_2$

[d] Levelized basis = 10 Mt/y CO$_2$ less 0.55 Mt/y CO$_2$ (0.90 Mt/y CO$_2$) for emissions associated with natural gas (coal) firing.

ESTIMATED COST OF A PILOT EXPERIMENT ON IN SITU CARBON MINERALIZATION IN PERIDOTITE OR BASALT

TABLE F.3 Timeline and Budget, Generic In Situ Carbon Mineralization Experiment in Peridotite or Basalt at 100,000 Tons/y

	Scoping and site selection		**Preparation for 2 years**		**Drilling**	**Injection for 2 years**		**Monitoring and analysis for 3 years**			
	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	Total
Management	$250,000	$250,000	$750,000	$750,000	$1,000,000	$1,000,000	$1,000,000	$750,000	$750,000	$750,000	$7,250,000
Characterization (mapping, small test wells)	$750,000	$750,000	$750,000	$750,000							$3,000,000
Injection preparation			$2,000,000	$2,000,000							$4,000,000
Drilling 1 injection well at $6M and 3 monitoring wells at $3M				$3,000,000	$12,000,000						
Permitting/outreach/ engagement	$250,000	$250,000	$250,000	$500,000	$208,333	$208,333	$208,333	$208,333	$208,333	$208,333	$2,500,000
Monitoring				$500,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$750,000	$750,000	$10,000,000
Research			$500,000	$1,000,000	$1,416,667	$1,416,667	$1,416,667	$1,416,667	$1,416,667	$1,416,667	$10,000,000
CO_2 at $100/ton				$100,000	$4,950,000	$4,950,000					$10,000,000
Contingency at 30% of total costs above	$375,000	$375,000	$1,275,000	$2,580,000	$6,472,500	$2,872,500	$1,387,500	$1,312,500	$937,500	$937,500	$18,525,000
Total	$1,625,000	$1,625,000	$5,525,000	$11,180,000	$28,047,500	$12,447,500	$6,012,500	$5,687,500	$4,062,500	$4,062,500	$80,275,000