Carbon180

formerly CENTER FOR CARBON REMOVAL

BUILDING A NEW CARBON ECONOMY

An Innovation Plan

A Product of the New Carbon Economy Consortium

The New Carbon Economy Consortium (NCE) is an alliance of universities, national labs, and NGOs partnering to enable a carbon-removing world.

Launched in 2017, the Consortium connects and supports individuals from across institutions and disciplines to pose new research questions, establish shared resources, and articulate pathways to the broad implementation of carbon removal solutions. This executive summary and the accompanying innovation plan mark the Consortium's first endeavor together and aims to consolidate the group's priorities for future research activities.

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OUR VISION

Today, a great resource lays underutilized.

While carbon emissions are largely considered a pollutant, emerging innovative technologies and land management practices hold the potential to transform carbon in the atmosphere into a valuable, productive resource. Combined with increasingly abundant clean energy and insights into the roles carbon plays in soils, human ingenuity and innovation can enable a previously unimaginable vision: a prosperous, growing economy that captures and stores more carbon than it emits. This economy shifts away from our history of extraction and degradation towards a future where we harness our lands to boost crop yields and soil health and transform carbon emissions into better chemicals and building materials. Under this revolutionary paradigm, new and reimagined industries can provide jobs, economic opportunity, and prosperity, all while mitigating climate change and supporting other important environmental goals.

DEFINITION

NEW CARBON ECONOMY (n.)

a prosperous, growing economy that captures and stores more carbon than it emits

The New Carbon Economy Consortium brings together fourteen academic institutions, national laboratories, and NGOs under this unified vision. Success, however, is not inevitable; significant knowledge gaps and challenges remain. Public and private capital currently offers little support for technological and land management innovation and nearly nonexistent incentives to bring these technologies and practices to scale. Overcoming these barriers and changing the status quo will require a monumental shift in the way we pursue the innovation agenda around carbon.

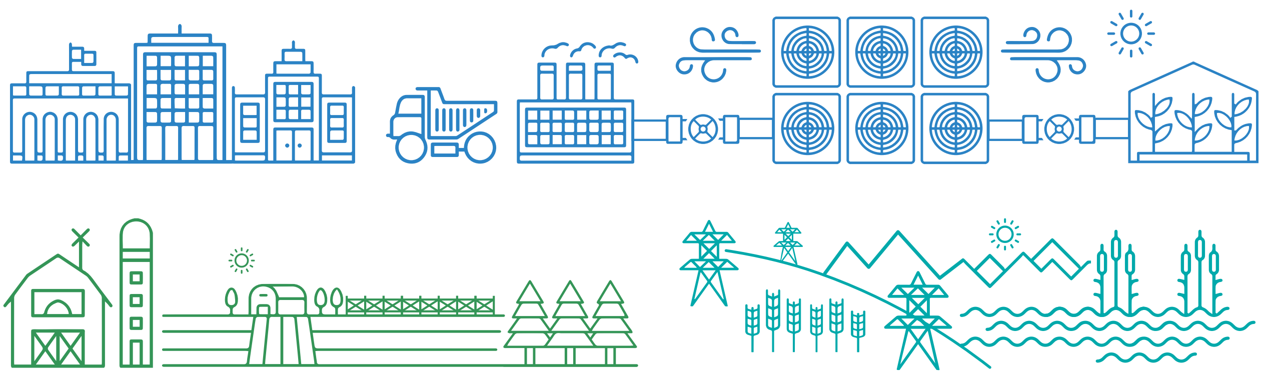
To realize this shift, we must start building the foundation for a new carbon economy today. This innovation plan outlines the contours of that foundation, by recommending promising research focus areas for three solution pathways and critical research infrastructure needed to bring the new carbon economy to fruition. This document marks the first collective endeavor of the New Carbon Economy Consortium and will serve as a foundation as we seek additional resources and partners.

OUR FRAMEWORK

The knowledge base of the new carbon economy spans many disciplines and economic sectors. The Consortium has identified three primary innovation pathways, each including carbon removal, that hold the greatest potential to activate the new carbon economy. We built this report around these three pathways, and their accompanying research avenues:

FIGURE 1. *Solutions in a New Carbon Economy*

The knowledge foundation of the new carbon economy spans many disciplines and economic sectors.



ENGINEERED SOLUTIONS, which include technologies and systems that capture, convert, and store CO_2 from the air and oceans, such as direct capture of CO_2 from air and point sources, converting CO_2 into valuable products (e.g., concrete or fuels), and the accelerated mineralization of CO_2 for sequestration.

BIOLOGICAL SOLUTIONS, which include the use of working forests and farmland to store carbon, increase yields, and improve ecosystem functions. Biological solutions include ecosystem restoration, improved forestry practices, changes in agricultural practices, developing soil amendments that improve soil health, and cultivating and converting algae into valuable products such as fertilizer and animal feed.

HYBRID SOLUTIONS, in which biological and engineered pathways come together to create energy and/or products. Hybrid energy solutions can include bioenergy with carbon capture, biochar production, waste-to-energy systems, and carbon-cultivating aquaculture.

In this innovation plan, we present a detailed exploration of each innovation pathway and its related solutions. From there, we identify the existing technical gaps, pinpointing high-priority areas for research over the short, medium, and long terms. First, we describe efforts that can start today to provide the information that is critical to enable early successes within a few years. Second, we propose work that requires more time to develop but that can provide large, meaningful outcomes in less than a decade. Finally, we outline additional foundational elements that will take at least a generation to bring to fruition and ultimately serve as an enduring knowledge substrate.

FIGURE 2. *Technical Chapter Structure*

Chapters 3-5 of the accompanying innovation plan identify promising solutions and research gaps to be addressed in the next thirty years. The research needs described for each innovation pathway feed into the final recommendations of the report and will guide the Consortium's first undertakings.

While the bulk of this document focuses on laying out a technical research plan, we recognize a need for major scholarship in legal, socioeconomic, and policy fields to complement and augment the technical tracts. This is particularly noteworthy where communities of practice are key to acceptance (e.g., by farmers in agronomy practices), where societal acceptance is a key component of success (e.g., carbon capture and storage), and where economic and policy incentives can catalyze deployment at scale. Many topics in the new carbon economy are inherently interdisciplinary, and thus require a combination of research topics and approaches to bring solutions to market. Therefore, research related to a new carbon economy would greatly benefit from integrating across conventional academic silos to incorporate scholarship from both technical and socioeconomic fields.

OUR FINDINGS AND RECOMMENDATIONS

Based on the technical gap identification and suggested research priorities, our innovation plan ends with an outline of the additional resources and infrastructure needed to enact this ambitious agenda. The following findings and recommendations will serve as the guiding principles for setting up the Consortium's core functions over the coming years.

CLOSE THE RESEARCH GAP. As evidenced by this report, there is a significant lack of integrated technical and socioeconomic knowledge related to the new carbon economy. Today, there are few research and development programs dedicated to filling this knowledge gap, and the ones that do receive insufficient funding to spur the significant breakthroughs required. One emergent recommendation is that the US federal government should substantially expand existing research programs related to the new carbon economy and build any other necessary research and training programs from scratch. Philanthropy, civil society, and industry have a large role to play in supporting the creation of a New Carbon Economy Consortium Secretariat to coordinate research, as well as translate relevant findings into business and policy action.

SHARE SUCCESSES—AND FAILURES. Current opportunities to catalyze research in carbon removal, especially those that can provide foundational information and early successes, can greatly benefit from discussion and knowledge-sharing early and often, both in person and virtually. Because many of the key research avenues to develop a new carbon economy inherently require partnership among technical and social science experts, it will be important to provide platforms for interdisciplinary translation and collaboration.

LAY THE ACADEMIC GROUNDWORK. Enacting this ambitious research agenda and bringing forth successful carbon removal solutions requires expertise that does not yet fully exist. Academic institutions need to develop curricula and academic programs at the intersection of relevant fields, and help build and train the workforce of tomorrow. Creating interdisciplinary research and training clusters, professional development opportunities, fellowships, and courses that address those pathways is critical to the new carbon economy.

BUILD THE CARBON-REMOVAL NETWORK. Finally, while assets and infrastructure related to carbon removal partially exist today, they are often distributed and isolated from interested parties in science, business, and policy. In addition, current frameworks and standards for evaluating carbon removal pathways are highly fragmented and inconsistent, creating uncertainty and hindering the deployment of solutions. Coordinated investment in research infrastructure and developing common standards for the Consortium to share can alleviate these barriers. Since managing carbon is essential in a new carbon economy, it is crucial to continue to develop and improve templates for measurement and verification, lifecycle analyses, and techno-economic comparison. These frameworks can be accompanied by a coordinated network of testbed projects across geographies to evaluate the performance and efficacy of carbon removal pathways in varying social contexts, climates, and ecosystems. The New Carbon Economy Consortium should work to establish and support new platforms to facilitate data compilation, standardization, aggregation, and distribution. To ensure the research agenda will be successfully coordinated and implemented, the Consortium should develop centers of excellence to help support and maintain the research infrastructure critical for scaling up the new carbon economy.

FIGURE 3. *Findings and Recommendations*

Significant work is required to realize a new carbon economy. Based on the technical gap identification in Chapters 3-5, we recommend a series of activities to be pursued by the Consortium and other institutions over the coming years.

	FINDINGS	RECOMMENDATIONS
KNOWLEDGE AND RESOURCE GAP	• There is a fundamental gap in integrated knowledge related to strategies for building the new carbon economy • There are very few R&D programs supporting key elements of the new carbon economy, and their funding level is insufficient to deliver breakthroughs	• Widen the range of R&D programs serving the new carbon economy and increase their funding • Create a New Carbon Economy Secretariat to rapidly gather and fund research teams, disseminate information, and prepare reports on the state of the new carbon economy and its components
LIMITS TO OPPORTUNITY	• Every discipline pertinent to the new carbon economy includes near-term, high-impact endeavors that are not fully mapped • There are limited fora to discuss and address R&D needs in all new carbon economy disciplines • Many topics in the new carbon economy are inherently interdisciplinary and, in many cases, require a mixture of "bench," field, and social science approaches to bring key opportunities to markets and stakeholders	• Select topics and teams to map national and global opportunities for research, development, and demonstration of key new carbon economy pathways • Convene disciplinary and interdisciplinary meetings and fora around the central topics holding back the emergence of the new carbon economy
HUMAN CAPITAL	• There are few programs that train experts in the integrated disciplines of the emerging new carbon economy	• Create interdisciplinary clusters and courses that address new carbon economy topics • Establish training programs to support research and human capital development focused specifically on the new carbon economy
COLLABORATION AND SCIENTIFIC INFRASTRUCTURE	• Although assets and infrastructural elements for the new carbon economy partially exist today, they are distributed and often isolated from interested researchers, leaders of research institutions, business leaders, and policymakers • The lack of consistent frameworks and standards for discussing and measuring the techno-economic and carbon-sequestering potential of solutions limits their uptake and deployment	• Develop platforms and test beds to analyze carbon uptake, utilization, and storage, and create templates for measurement and verification, lifecycle analyses, and techno-economic comparison • Create and support new platforms to compile, aggregate, analyze, and share data • Sponsors and host institutions should create and support centers of excellence for new carbon economy studies

CONCLUSION

As this innovation plan makes clear, the promise of the new carbon economy is great. And yet, a fundamental gap exists between our current knowledge and what we need for a new carbon economy to flourish. Few research and development programs exist today to supply that knowledge, and most are too under-resourced to achieve national or global impact. Without a concerted research and deployment effort, we will never realize the potential of the recommendations and findings outlined here. No single academic institution or national lab is equipped to take on this challenge alone. Together, the New Carbon Economy Consortium has the power and expertise to not only formalize the innovation plan laid out in this document, but to move forward to execute it. The benefits from economic growth, new industry creation, and equal access to opportunity will manifest only through investment and commitment to that vision. We hope you will join us in building the new carbon economy.

To read the full innovation plan, please go to **www.carbon180.org/newcarboneconomy**

For questions on the New Carbon Economy Consortium, please contact **giana@carbon180.org**.

Chapter 1: Introduction

VISION

Today, we stand at the dawn of the new carbon economy.

Emerging innovative technologies and land management practices hold the potential for developing a “new carbon economy” – a robust economy in which waste carbon in the atmosphere is transformed into valuable and productive resources and stored in our lands, built environment, and abundant geologic reservoirs. These innovations can support a growing, prosperous economy that harvests and stores carbon from the air, all while mitigating climate change.

DEFINITION

NEW CARBON ECONOMY (n.)

a prosperous, growing economy that captures and stores more carbon than it emits

This new carbon economy offers opportunities to create a new path forward—one where existing industries are revitalized and new industries are built to be more environmentally sustainable, resilient, and economically competitive. Forestry and agriculture can expand and enhance our natural and working lands and build rich fertile soils that boost yields *and* environmental services. Industry can evolve from a long history of extraction and waste generation to a future of innovation and reuse, recycling carbon emissions into new materials and providing new services to dispose of carbon emissions.

The path to the new carbon economy also offers immense potential for communities around the globe, built to ensure a more equitable, just, and environmentally conscious world. Rural and industrial communities alike will create new, more resilient jobs and businesses. Investors and corporations will expand existing products and markets as they transition to more environmentally and climate-friendly business practices. Policymakers will find common ground proactively supporting environmental and climate policies. Innovation to power the new carbon economy will be transformative, much like the invention of the Global Positioning System, the internet, and accelerometers that power the smartphones embedded in the fabric of our modern society.

THE CHALLENGE

The new carbon economy is not inevitable; it must be built. While many of the biological pathways to the new carbon economy are ready to deploy, social and economic incentives are needed to hasten their widespread adoption. Major technological advances are also needed for monitoring and accounting for carbon in living systems. For engineered solutions, many of the technologies that create value from carbon emissions are too expensive today, absent policy incentives and market access.

Overcoming the challenges that inhibit the development of the new carbon economy will require research and development at a scope and scale that far exceeds current activity. Today, such activity is scattered, siloed, and poorly funded. Bottlenecks have not been identified or removed as fast or effectively as is needed. Data and outcomes have not been shared widely or translated into policies, business models, and commecial activity. Scientists, policymakers, and business leaders have not received the training necessary to create a range of career and leadership opportunities that are needed to support the new carbon economy.

Finally, no single institution or sector of society is equipped to overcome these challenges and move forward at the scale and pace required. Similarly, no single federal agency or congressional committee has the breadth to cover all the integral elements. A new research endeavor—one that is distributed, multidisciplinary, and flexible—is needed to realize the vision of a vibrant new carbon economy.

THE NEW CARBON ECONOMY CONSORTIUM

Inspired by this vision and cognizant of the scale and nature of the challenges, a number of universities, national labs, nonprofits, and businesses have come together to work toward a new carbon economy. Together, this group formed the *New Carbon Economy Consortium*. The Consortium aims to function as a distributed, multidisciplinary laboratory for carbon, with a focus on removing the barriers standing between our world today—in which research and development of carbon removal technologies and approaches is dispersed, uncoordinated, and underfunded—and solving the problems that are preventing the realization of the thriving new carbon economy.

The Consortium, over the coming years, will build a foundational knowledge enterprise for the new carbon economy. This knowledge enterprise will include the hard science and engineering needed to:

- Understand, measure, and enhance the complex cycling of carbon in our natural systems;
- Invent the technologies to separate carbon from dilute sources and convert it into valuable products in an economically viable manner; and
- Find novel ways of locking up carbon from the atmosphere.

The Consortium will also explore the critical intersection between such technological advancements and the social, economic, and political sciences. Crucially, it will support the education, training, and knowledge base needed to translate academic research into real-world transformation.

As a first step in charting the course toward the new carbon economy, the Consortium collaborated on the innovation plan that follows. The goal of the plan is to 1) define key short-, mid-, and long-term research questions, and 2) propose collaborations to catalyze the discovery and innovation upon which the new carbon economy's carbon removal solutions will depend. The innovation plan was developed with participation from experts working on carbon cycling and materials chemistry, engineers working on systems design and bioengineering, and economists, business experts, and social and political scientists whose research is essential in the new carbon economy, and it calls for additional engagement and collaboration. Founding participants represented the following institutions: Center for Carbon Removal (convener), Arizona State University, Colorado School of Mines, Colorado State University, Columbia University, Cornell University, Howard University, Purdue University, University of British Columbia, University of Wyoming, Lawrence Livermore National Laboratory, National Renewable Energy Laboratory, Sandia National Laboratories, and the Energy Futures Initiative.

While the eventual shape of the Consortium is still under development, many of its contours are clear. First, the Consortium seeks to execute the knowledge enterprise at the heart of the new carbon economy, not just design as laid out in this innovation plan. To do so, the Consortium could serve a number of functions that are currently unmet:

- Catalyze "outside-the-box" thinking by bringing together groups, researchers, and disciplines that do not traditionally work together
- Mobilize funding for such interdisciplinary, multi-institution research collaborations
- Build research infrastructure, including networks of testbeds and open source databases that are essential foundations for rapid iteration (succeeding or failing quickly)
- Support the next generation of carbon removal innovators and practitioners via fellowships, interdisciplinary training, communications training, and access to research infrastructure
- Convene events and develop thought leadership to foster dialogue and collaboration across all aspects of the new carbon economy

The Consortium hopes to build membership beyond those involved in this initial innovation plan. The Consortium seeks to include relevant researchers in this enterprise and collaborate beyond North America as priorities coalesce and funding begins to materialize.

Chapter 2: Welcome to the New Carbon Economy Innovation Plan

OVERVIEW

This innovation plan aims to provide a dynamic blueprint for how research institutions can collaborate to build a new carbon economy and present the complex and often highly technical research challenges involved to a wide range of audiences, including everyone from researchers searching for new technical challenges to tackle, to policymakers, philanthropies, and businesses looking to the guide research investment and future priorities.

Specifically, this plan presents:

- A focused analysis on promising carbon removal pathways that have the capacity to deliver economic value in the long run;
- The key research-and-development (R&D) challenges facing pathways to a new carbon economy;
- A proposed sequencing of tasks to accelerate innovation and maximize impact of R&D efforts;
- Specific recommendations for R&D projects in each area;
- The mid- and long-term research needs in each area and, where appropriate, how early R&D endeavors can form the necessary foundation for future work; and
- A set of recommendations for research administrators and funders for catalyzing the emergence of a new carbon economy.

SCOPE

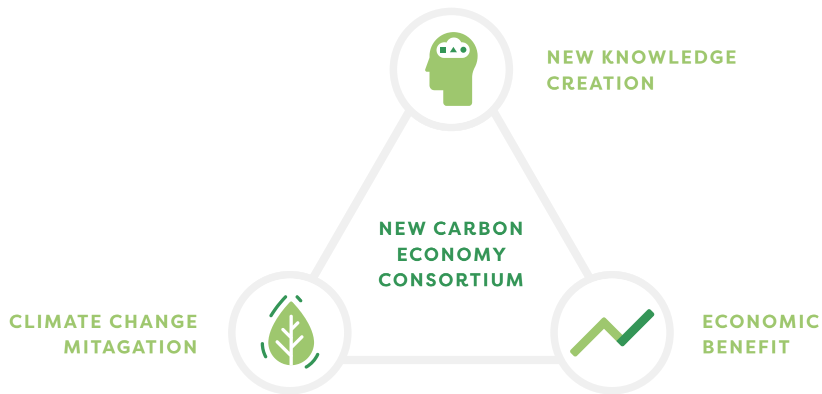
The new carbon economy will involve many components, including land management and industrial solutions that capture and sequester atmospheric carbon. Other advances—including breakthroughs in clean energy production, artificial intelligence, biological engineering, additive manufacturing, and nanotechnology, to name just a few—can also contribute to the emergence of a new carbon economy.

To keep the scope of this innovation plan manageable and additive to existing research roadmaps, this analysis focuses on carbon management pathways with a potential for delivering carbon removal and economic value in the long run. Specifically, this plan focuses on research related to solutions pathways that meet three main criteria:

- Can remove CO_2 from the atmosphere in large volumes relatively rapidly
- When deployed, create economic value
- Require substantial new research or innovation over the next 30 years of scale-up—that is, needs the Consortium's visionary support

FIGURE 4. *Consortium Focus Areas*

The New Carbon Economy Consortium serves to advance and support engineered, biological, and hybrid solutions in their capacity to provide an economic and climate benefit, through the creation of new knowledge.

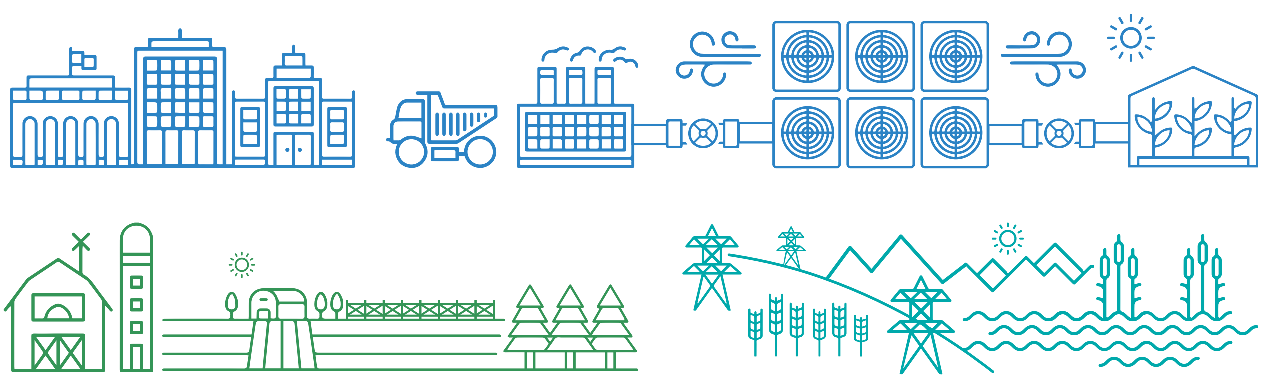


STRUCTURE

The innovation plan then divides the solutions in scope into three interconnected categories:

FIGURE 5. *Solutions in a New Carbon Economy*

The knowledge foundation of the new carbon economy spans many disciplines and economic sectors.



ENGINEERED SOLUTIONS (CHAPTER 3): Practices and technologies that remove CO_2 from the air and oceans and create economic value by the manufacture of products or carbon removal services

BIOLOGICAL SOLUTIONS (CHAPTER 4): Practices and approaches that remove carbon from the atmosphere and improve the ecological and economic sustainability of managed biological systems, such as agriculture, forestry, and grazing.

HYBRID SOLUTIONS (CHAPTER 5): Practices and technologies that require integration of technology and biology to yield services and products from biomass and net carbon reduction to the air and oceans.

Each chapter is similarly structured to introduce the most promising solutions identified by the Consortium team and the knowledge gaps that can be addressed with a targeted R&D agenda. Research priorities are given for the near, medium, and long term across technical and social dimensions. Much of the research to bring about the new carbon economy is cross-cutting, and each chapter identifies opportunities for integration with other technical chapters. Each chapter concludes with recommendations for early research projects for the Consortium to undertake and support, as well as a section on how the Consortium can support human capital development in relevant fields.

Importantly, detailed funding recommendations are not provided within the technical chapters or final recommendations. Assessing the appropriate programatic and fundings needs in each new carbon economy area is outside the scope of this innovation plan. To accomplish that programmatic effort, we believe a substantial engagement of a broader community of scientists, practitioners, and experts is required. However, it is likely that substantiual new R&D funding is required to enact the research agenda presented in this innovation plan and scale a new carbon economy.

A key feature of this innovation plan is the proposed sequencing of research activities into short-, mid-, and long-term priorities. All of these research avenues are urgent and must begin today concurrently, but the suceess of some are contingent upon the findings of others, and some research topics are closer to completion. Therefore, *research across all the listed priorities should begin immediately.* Sequencing of near-, mid-, and long-term projects indicates contingencies on exogenous social, political, or economic factors, reliance on other research findings, and the creation of new infrastructure. Criteria for prioritization of activities across timescales follow:

FIGURE 6. *Temporal Structure of Research Needs*

SHORT TERM RESEARCH NEEDS (1-3 YEARS)

- Research that solves problems holding back solutions at or near high technological readiness levels
- Solutions that have a commercial market today but need additional research to reach full potential
- Activities that answer bottleneck questions needed to inform future research
- Projects that build the infrastructure needed (e.g., testbeds, databases, standards and protocols, etc.) to enable and scale further research

MID TERM RESEARCH NEEDS (3-10 YEARS)

- Research that depends on discoveries and progress in the near term
- Research for strategies that require more time to be developed and commercialized
- Research for strategies that depend on exogenous factors, such as policy or market access

LONG TERM RESEARCH NEEDS (10-30 YEARS)

- Research into solutions that add substantively to long-term climate change mitigation and offer considerable economic opportunities
- Research that depends on new infrastructure and technological breakthroughs
- Research that depends significantly on findings from near-term and mid-term research priorities

Many of the proposed R&D tasks could facilitate early deployment, ideally commercial scale or near-commercial scale. Such recommendations are atypical of traditional R&D roadmaps. In this innovation plan, the Consortium aims to accelerate and shorten the R&D pipeline where appropriate to gain knowledge and iterate more quickly. Some knowledge and experience requires deployment to gain field information and learning by doing.

The innovation plan concludes with recommendations for advancing the knowledge enterprise needed to build the new carbon economy. These recommendations aim to synthesize the content in the technical chapters and provide a cross-cutting and consolidated set of ideas for how researchers across institutions, geographies, and disciplines can begin collaborating to advance the research priorities outlined in this innovation plan.

FIGURE 7. *Technical Chapter Structure*

Chapter 3: Engineered Solutions

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INTRODUCTION

In the new carbon economy, engineered solutions will be essential enablers of creating value from carbon. Removing CO_2 from the air and oceans and converting it to beneficial products or storing it reliably will require new knowledge and technologies. A thriving new carbon economy calls on us today to begin bridging important gaps between our current and future technological capabilities.

Three tasks frame the challenge:

- **CAPTURING AND REMOVING CO_2** from the air and oceans, as well as emissions associated with conventional sources of energy and heavy industry (e.g., steel and cement)
- **CONVERTING AND USING CO_2** as feedstocks for construction materials, fuels, and chemicals
- **STORING CO_2** via rapid mineralization at the Earth's surface or in deep geological formations

The physics and chemistry of these tasks can also be represented as three sets of activities: capture CO_2 from a concentrated source (e.g., power plant) or dilute source (e.g., the air); use CO_2 in oil production (e.g., enhanced oil recovery) or novel products (e.g., carbon fiber); and store CO_2 in conventional formations (e.g., geological features, oilfields, or saline formations) or in new forms (e.g., mineralization). Of this matrix of possibilities, only conventional carbon capture with enhanced oil recovery (EOR) is fully mature today. This provides opportunity for innovation in all the other tasks.

Several key areas stand out as critical pathways, as recognized in the recent "U.N. Environment Emissions Gap Report" and the National Research Council's "Carbon Dioxide Removal and Reliable Sequestration (2015)" report: direct air capture (DAC) with reliable CO_2 storage or CO_2 use, accelerated weathering and mineralization, and CO_2 conversion to products. Almost all CO_2 capture and use approaches face a material science challenge: There is a broad need to develop new catalysts, electrolyzer anodes, and membranes. Each pathway has special needs and considerations, including technological readiness, market readiness, the degree to which it requires significant energy inputs or produces waste heat, and the value of resulting products.

RELATED ROADMAPPING EFFORTS

The treatment of engineered solutions in this chapter builds upon but is different from existing carbon capture and storage R&D roadmaps. These include the "CURC-EPRI Advanced Fossil Energy Technology Roadmap," the U.S. DOE Office of Science's 2009 "Basic Research Needs" report, and the Carbon Sequestration Leadership Forum's "Technology Roadmap 2017." These efforts commonly focus on carbon capture R&D for large-scale power generation and industrial applications, coupled with conventional geologic storage. Recently, the Innovation for Cool Earth Forum published two CO_2 utilization roadmaps (2016 and 2017), which represent an overview of a carbon utilization R&D agenda. Finally, the U.S. National Academies of Sciences is finalizing a report, "Carbon Dioxide Removal and Reliable Sequestration," which includes a detailed summary and R&D agenda for geologic carbon storage.

The focus of this innovation plan for a new carbon economy expands upon and complements previous roadmaps in three main ways: 1) it presents a promising research agenda for carbon management pathways, such as direct air capture and carbon utilization approaches, which emphasize economic opportunity and scaling to market; 2) it links research and deployment avenues where possible to scale more quickly, in some cases emphasizing early deployment as an opportunity to learn by doing and gather field data; and 3) it explicitly discusses key R&D infrastructure needs, such as testbeds and centers of excellence that can provide key information and develop human capital. As this work evolves, future innovation plans can refine and expand upon these topics with new scholarship and programatic direction.

MOST PROMISING CARBON REMOVAL APPROACHES AND KEY RESEARCH NEEDS

From the range of potential research avenues, the innovation plan focuses on three sets of engineered solutions because they hold economic potential and climate and environmental benefits: direct air capture (DAC), CO_2 conversion and use (CO_2U or carbon-to-value), and accelerated weathering and mineralization.

DIRECT AIR CAPTURE

OVERVIEW AND KNOWLEDGE GAPS

Direct air capture—the process of separating CO_2 from air or seawater—faces one central technical challenge: low CO_2 concentration. Remarkable recent progress, including the creation of several companies and commercial projects, validates that DAC is technically and economically feasible, with almost immediate applications. Key applications include the food and beverage market, carbonate and urea production (Boot-Handford et al. 2014), enhanced oil recovery, carbon-removal services, and CO_2 conversion to products for large markets, such as concrete and other carbonaceous building materials, commodity chemicals, and fuels. However, succeeding at scale requires materials, devices, and systems beyond what exist today. Most importantly, it requires substantial cost reductions to less than $100 per ton. Today's costs are substantially higher, at $400-600 per ton.

The high costs of direct air capture are the consequence of low CO_2 concentration. Large-scale deployment of DAC requires increases in energy efficiency and reduction in cost. Both can be greatly improved with new and better contactors, such as solvents, sorbents, and membranes, that can separate CO_2 from air or ocean at a large volume and be affordably built and operated. Also, the input energy required to reconstitute and concentrate CO_2 must be extremely low and nearly carbon free—much lower than today's conventional carbon capture technology.

Increasing DAC efficiency and reducing costs require novel designs, materials, and approaches to operation and integration, important both for the individual technologies and because innovations in one device or system can lead to reduced costs and increased energy efficiency in others. In the near term, DAC will need policy or price support to reduce costs and learn through deployment and scale-up.

TECHNICAL R&D PRIORITIES

A substantial deployment of DAC in commercial markets requires a large innovation agenda. Although some aspects of that agenda could deliver near-term opportunities or set the stage for future improvements, some work will take many years to reach fruition. However, all areas of innovation should commence now to maximize benefit and reduce risks, including areas that may take decades to maximize progress.

NEAR-TERM R&D PRIORITIES (1-3 YEARS)

DEVELOPMENT OF HIGH SURFACE AREA CONTACTORS: Due to low air CO_2 concentrations, DAC systems must physically contact a large volume of air over a large surface area. We need new contactor configurations that provide greater reactive surface area, have low capital costs, and can be fabricated from earth-abundant material and readily shipped and deployed (contactors are a rate-limiting step for subsequent system development). Promising pathways include using biological surface templates, 3D printing and advanced manufacturing, metal organic and covalent organic frameworks, and functionalization of aerogels and xerogels.

DEVELOPMENT OF EFFICIENT CARBON CAPTURE MATERIALS: Capturing CO_2 from dilute sources often requires strong binding energy or driving force. While there are several novel carbon capture materials being developed (both liquid and solid), there is a strong need for the development of more efficient carbon capture materials specifically targeted for DAC or capturing CO_2 from dilute gas streams.

MAPPING HIGH-VALUE PROJECT OPPORTUNITIES: Areas of opportunity, resource overlap, and systems integration need to be mapped to give project developers targets for action. DAC has the benefit of being possible anywhere on the Earth's surface, potentially eliminating transportation costs and capital if CO_2 can be utilized or stored through geological storage on-site. However, to truly be a carbon removal technology, CO_2 emissions from DAC must effectively be net zero, meaning that zero-emissions heat and power (e.g. renewables, nuclear, zero-carbon hydrogen) are required for operation. DAC can provide a potential commercial opportunity in locations where zero-carbon energy coincides with potential offtakes. Identifying and qualifying such regional "sweet spots" is a top-tier, near-term R&D priority as it provides targets for subsequent strategic action.

MID-TERM R&D PRIORITIES (3-10 YEARS)

DEVELOPMENT OF ULTRA-LOW ENERGY CAPTURE SYSTEMS: DAC is cheaper and has a smaller footprint when capture and recovery systems use little energy or can rely on zero-carbon renewable heat and power. Designs with passive flow, low barriers to activation, and enhanced kinetics should all be developed and coupled with better materials, improved cycle efficiency, and new solvents, sorbents, and membranes. Integrating DAC systems with variable renewable power generation could provide benefits for grid operators and power developers who can capitalize on curtailed power to drive the DAC cycle.

LOW-CAPITAL FABRICATION OF DAC MACHINERY: One of the steepest challenges for any CO_2 capture system is the high upfront capital. Additive manufacturing (e.g., 3D printing) can reduce material utilization and limit reliance on supply chains. Costs can also be lowered through the replacement of metals with polymers (facilitated by low-temperature and nonpressurized reactors), the use of low-cost production methodologies for carbon fiber and composites, and the introduction of mass-manufacturing techniques.

REACTIVE MINERALS AS AN ACCELERANT TO DAC: The cost of capture is also lower when associated with mineralization (i.e., exothermic reactions in existing geological materials). Potential reactive geological formations that could serve as reactive agents with air should be explored, and methods must be developed to create and sustain long-term fluid flow pathways and expose and maintain reactive surface area.

LONG-TERM R&D PRIORITIES (10-30 YEARS)

DIRECT OCEAN CAPTURE: Ocean acidification remains a direct and present danger to global ecosystems and human health. Mitigation approaches are few, including directly separating CO_2 from ocean brines (direct ocean capture) or indirect approaches such as rebalancing the atmosphere, which would also rebalance the ocean. Direct ocean capture methods will require novel CO_2 separation approaches suited to the ocean and maritime applications (for example, submersible contactors and separation reactors or integration of direct ocean capture with aquaculture), and they must tackle the related marine application challenges (such as microbial biofouling and marine ecosystem degradation). Promising approaches include CO_2-brine separation membranes and ocean alkalinity enhancement, and a key application is the byproduct precipitation of carbonate minerals to add sediments to ecosystems or provide local operators with building materials.

INTEGRATION OF DAC INTO EXISTING AIR-HANDLING INFRASTRUCTURE IN INDUSTRIAL AND COMMERCIAL FACILITIES: As one approach to reduce capital costs, DAC components or materials could be integrated into distributed systems such as industrial or commercial heating, ventilation, and air conditioning systems or in desalination plants. These have particular challenges associated with form factor, balancing operational needs, control systems, and other site- and tech-specific issues. Research is needed to determine the viability of such systems and design new systems that accomplish multiple needs in the same capital device.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

DAC and direct ocean capture immediately prompt a set of socioeconomic considerations. The issue of governance is important: Local and national actions provide a global benefit but require local resources and must be balanced against other local and national needs (e.g., NDCs or energy access). Similarly, if DAC becomes relatively low cost ($60-150/ton), many regulatory options become available for managing compliance with emissions taxes or caps. Other new carbon economy engagements (for example, afforestation, which is discussed in Chapter 4) provide important lessons learned for policy, economic, and social considerations for advancing new carbon economy pathways, and collaboration among social science researchers across natural and engineered pathways can provide important insights for developing both sets of industries. Many efforts to deploy carbon capture require a mix of technical and social science disciplines (economics, behavioral science, decision support tools). Traditional R&D programs do not fund social science adequately; differences across technical cultures also limit collaboration opportunities. New and/or expanded platforms that encourage interdisciplinary work around the new carbon economy, especially those that feature both technical and social science disciplines, are needed to make rapid progress in developing carbon removal pathways that are economically feasible and can overcome challenges limiting their adoption.

CO_2 CONVERSION AND USE (CO_2U): CARBON-TO-VALUE AT SCALE

OVERVIEW AND KNOWLEDGE GAPS

CO_2 conversion and use, also referred to as CO_2U or carbon capture and use (CCU), creates products that can generate revenue—doing well by doing good (also called carbon-to-value). These pathways have the potential to create new manufacturing and industrial bases in the new carbon economy while reducing or removing carbon pollution.

Like DAC, CO_2 conversion and use faces a material science challenge, with a strong need to develop new catalysts, electrolyzer anodes, and membranes. Lifecycle analysis and policy support are also needed for CO_2U approaches to achieve climate goals and substantial market penetration. Even with improved policy and analytic support, an innovation agenda is required to improve the cost, performance, and net carbon reduction of CO_2U. New standards and certification should be developed for these products to accelerate their deployment into each sector described below. Three general sectors of varying market size and degree of readiness show significant promise.

CONCRETE AND OTHER CARBONACEOUS BUILDING MATERIALS: Cement and concrete are the most common building materials on earth, representing a $1 trillion market. Cement production is also one of the largest emissions sources due to the heat required to make it and the CO_2 released from the process. In the near term, there are opportunities to develop and deploy utilization of CO_2 for cement and other building materials, improving overall efficiency and carbon uptake while lowering costs. There are two main pathways: 1) use of CO_2 in cement curing, and 2) direct use of synthetic carbonate products as aggregates for construction materials. This CO_2U pathway has large market potential and helpful thermodynamics: The processes do not require significant energy inputs and produce potentially useful waste heat that can be harnessed. While the market value of concrete and other carbonaceous building materials is relatively low ($20-50/ton), their production is enormous; annual concrete production is in the range of 25 gigatons per year (Gursel et al. 2014). CO_2-derived materials can replace a highly carbon-intensive product and eliminate energy-intensive processes such as limestone calcination. Alkaline industrial wastes such as steel slags, red mud, and waste cement are currently being investigated as feedstocks, holding the potential to address multiple environmental issues and create important co-benefits.

COMMODITY CHEMICALS AND FUELS: Most liquid fuels are built of carbon, and their combustion releases CO_2. Similarly, many commodity chemicals (e.g., ethylene, methanol) are built of carbon, and their lifecycle use releases CO_2. Conversion of captured CO_2 back into chemicals or hydrocarbon fuels creates a circular economy that could approach carbon neutrality and, importantly, provide a pathway to significant avoided carbon emissions and market displacement of traditional fossil fuels.

Liquid transportation fuels will remain necessary for some time, especially for aviation and ocean shipping where replacement of hydrocarbon fuels is difficult; this represents a large market opportunity for synthetic liquid fuels made from CO_2. The fuels markets are large—more than 8 billion tons/year—with exceptional energy storage by mass and volume, transportability, fueling rate, and access to existing infrastructure. The creation of hydrocarbon fuels from DAC must have low energy inputs and use or directly integrate zero-carbon heat and power in order to reduce overall CO_2 emissions. This CO_2U could support deeper market penetration of variable renewables if it could operate the energy-intensive steps involved, such as electrolysis, which is coincident with low demand and can help manage both the variability of wind and solar and the clean energy transition (House et al. 2011; Kramer and Haigh 2009). To be profitable, such a process would yield products that ultimately must compete with sources of naturally available hydrocarbons.

The chemicals markets are relatively modest in CO_2 volume (on the order of 1 billion tons/year), but are an essential market segment with high-value economic activity. The fuels markets are much larger (more than 8 billion tons/year). In some cases, the technology or CO_2U is relatively mature; in other cases, such as for direct electrical reduction of CO_2, maturation is required.

There are potential benefits of colocation of multiple carbon removal and utilization technologies. DAC combined with electrical or thermal synthesis of fuels and chemicals can be used to export remote renewable energy in chemical form. These fuels and chemicals could be reformed to H_2 and CO_2 at market, enabling clean power or fuel with CO_2 sequestration (Fukuzumi 2017). If sent to regions with ample CO_2 storage capacity, this could enable negative emissions.

DURABLE CARBON MATERIALS: Although durable carbon materials, such as carbon composites or graphene, present small markets today, they have high market value, often surpassing $1,000/ton CO_2. This high price point offers an important first market for technology developers, especially since many of the technologies for direct single- or multistage conversion of CO_2 into carbon materials are in very early stages of development. Innovators can take advantage of these niche markets to gain revenues and learn by doing. For this enterprise to scale and have climate relevance, these materials must create new markets or displace existing materials in markets (e.g., substitution of carbon fiber for concrete). While the market potential of these materials may be quite large, it will require technological breakthroughs to enable low-cost fabrication; investments in small markets today might enable major industrial transformations in the future.

TECHNICAL R&D PRIORITIES

Near-Term (1-3 years) R&D Priorities

DEVELOPMENT OF TECHNOLOGIES AND STANDARDS FOR CEMENT AND CONCRETE PRODUCTION: As mentioned above, CO_2-enhanced concrete curing has already been demonstrated at some scale but requires further development. This work would need to demonstrate these metrics of performance:

- maturation, scale-up, and testing of advanced approaches
- development of feedstocks using earth-abundant materials and alkaline industrial wastes
- development of integrated material- and heat-recovery systems
- accelerated development of performance-based standards for market entry

It's also critically important to accelerate development of performance-based standards for market entry. Many procurement standards today are compositionally based (e.g., Portland cement only), which limits the R&D agenda severely. Testing of new cement and concrete formulations for compressive strength, tensile strength, longevity or corrosion resistance, for example, is essential technical work that empowers a new carbon economy.

LIFECYCLE ANALYSIS (LCA): The rate and volume of market penetration for CO_2-based products will almost certainly be tied to the carbon footprint based on standardized lifecycle analysis and comparison with fossil fuel-based products in the market. However, many of the pathways to make CO_2-based products, especially for chemicals and fuels, are very novel and lack core data to execute LCAs. Although the methodology for lifecycle analysis is well established, its application to CO_2U is extremely limited to date. Focused CO_2U lifecycle analyses are needed because some chemicals are anticipated as feedstocks for long-lived products (e.g., polymers), whereas others, such as fuels, are short-lived, and these complexities make it difficult to understand their climatic benefit and market value. Finally, each LCA of these approaches and methodologies is bespoke for each process and is often required for environmental product declarations. R&D is urgently required to automate data gathering and analysis for CO_2U to be policy and market relevant.

DEVELOPMENT OF ENHANCED THERMAL CONVERSION OF CO_2 TO FUELS AND CHEMICALS: Overall, substantial heat and power inputs are required to make fuels and chemicals for traditional markets. Today, the high maturity of several thermal conversion approaches suggests that they could enter the market more quickly than other approaches if total heat requirements were lower (Tuller 2017). The largest facility today converting CO_2 to methanol is just one-tenth the size of most methanol production facilities, illuminating the need for scale-up or modularization, including process intensification and integration. Cost improvements and better competitiveness are also needed through improved conversion efficiency, hydrogen production with reduced or zero-carbon emissions (e.g., advanced water splitting), utilization of waste heat, and the development of more selective catalysts, better-performing redox active metal oxides, and novel materials for combined capture and catalytic conversion.

OPPORTUNITY MAPPING FOR CO_2U PROJECTS: Some technologies and companies are close to pilot demonstration or scale-up, suggesting low-cost, high-readiness, high-impact early projects. A dedicated effort to map regional "sweet spot" opportunities is needed. For example, synthetic concrete projects will need to identify geographically colocated high-concentration CO_2 sources and local supplies of metal oxides, such as cement kiln and demolition waste dust, steel slag, and reactive fly ash. Similarly, CO_2-to-fuels projects need to be identified in areas possessing high-concentration CO_2 supplies, long and expensive logistic chains, high local fuel costs, and governments that have already identified CO_2U as a priority (e.g., Iceland and Japan).

Mid-Term (3-10 years) R&D Priorities

DEVELOPMENT OF "CLEAN HEAT" SOURCES: Focused R&D on novel, clean, zero-carbon heat production is essential to both deep decarbonization and a new carbon economy. Many CO_2U approaches require substantial low-quality heat (<150 C), high-quality heat (>300 C), or both. However, deployment is severly limited by availablility of clean, low-carbon heat sources, since the use of fossil heat may severely reduce or eliminate any CO_2 reduction benefit. Although several approaches have received some early work (e.g., novel solar concentrators, advanced heat pumps, microwave heat delivery, small modular nuclear reactors, methane-reformation to hydrogen + CCS), there are cost and performance challenges with all approaches. Targeted work on all methods and new ones will be necessary for scale-up and commercialization.

ELECTROREDUCTION OF CO_2 TO HYDROCARBONS + ALCOHOLS: Because methanol and ethanol have large markets and supporting infrastructure, fuels made from CO_2 represent a market opportunity today. Low-cost, abundant renewable power makes electrical conversion pathways increasingly attractive, and regions with good renewable power production will favor these approaches. However, multiple challenges must be overcome in one-step electrochemical pathways, including low efficiency, low-current density, low selectivity, and poor electrode stability. The ability to operate at low temperatures and low overpotential is desirable for coupling with distributed renewable sources. In addition, a "hybrid" electrolysis cell or "bioelectrosynthesis" with living microbial communities in the reactors has recently gained prominence and merits sustained R&D (Kracke et al. 2015; Pant et al. 2012; Köpke et al. 2011; Ou et al. 2013). Building on similar efforts, much more R&D is needed to better understand the relationships between electrode materials, their structure, and the fundamental mechanisms of CO_2 reduction. Finally, incorporating these approaches into existing electroyzer designs or developing new electrolyzers is required for scale-up. A major applied research and engineering design effort focused on this decade is needed to take advantage of the existing markets for hydrocarbons and alcohols, ideally in partnership with private entities.

ELECTROLYZER PRODUCTION OF SYNGAS: Great progress has been made in reverse fuel cells and electrolyzers that convert CO_2 to CO to fuels or chemicals, split water to generate hydrogen for feedstock, or directly make more exotic chemicals. However, questions remain about how to fabricate large volumes of the core reactors and conversion units. To move these technologies to market requires large-scale production of cells and electrodes (including developing high-throughput systems), improving longevity and performance, preventing corrosion and seal failure, and greatly reducing unit capital and operating costs. Substantial improvements may also be possible with high-temperature electrolysis, which requires R&D in systems integration and efficiency.

OTHER PATHWAYS TO CHEMICAL SYNTHESIS FROM CO_2 AND WATER: There are generally four classes of conversion technologies that can split water and split or reduce CO_2: low- and high-temperature electrolysis, photoelectrochemistry, and solar thermochemistry. Each class has unique upstream challenges regarding efficiency and durability at the scale of materials, devices, reactors, and systems. The challenge for downstream synthesis (given H_2 and CO_2 or H_2/CO mixtures) is selectivity and down-scaling reactors to a scale that matches the primary renewable resource used in producing the syngas.

DIRECT PRODUCTION OF GRAPHENE, CARBON FIBER, AND CARBON NANOTUBES: Some durable carbon products play key roles in aerospace, defense, construction, and manufacturing (including graphene, fullerenes, carbon nanotubes, carbon fiber, carbon composites, and carbon electrodes). Their high commercial value and broad application make them attractive early targets for production, and current progress suggests that direct production is possible within 10 years. Research must focus on new chemistries, surface chemistries, reactors, synthesis pathways, and manufacturing processes.

DIRECT CO_2 POLYMERIZATION: Today's polymers, such as polypropylene, cellophane, and polyvinyl chloride (PVC), are made from hydrocarbons. However, atmospheric CO_2 can be the feedstock for these valuable and widely used materials, with targeted R&D to reduce nonhydrocarbon feedstock costs, lower the amount of energy required, and reduce their overall carbon footprint.

INTEGRATION OF CO_2 UTILIZATION WITH EXISTING MANUFACTURING AND ENERGY SYSTEMS: For CO_2U pathways that generate heat while forming the product (i.e., cement and aggregate), economic margins are very tight and capital equipment expensive. In the shorter term, R&D can focus on generating extra value or revenues, such as finding ways to integrate new CO_2-based products into existing manufacturing systems or, conversely, to short-circuit transportation and supply chain costs. Endothermic CO_2U pathways have the additional challenge of needing to be integrated with or designed based on variable and intermittent renewable energy systems, ultimately the preferred energy source for CO_2-based products.

Long-Term (10-30 years) R&D Topics

FUNDAMENTAL MATERIAL SCIENCE INVESTIGATION: Almost all CO_2-conversion approaches face a material science challenge. Catalysts, high-temperature alloys, novel polymers (e.g., membranes), resins, perovskites, and other exotic materials can each serve to improve the cost, performance, and viability of CO_2 splitting or conversion and advanced water splitting. To make progress, an improved understanding of the foundational physics and chemistry of materials is needed, including better understanding of the core processes in molecular material behavior and construction. A multiyear, sustained basic science effort is needed for better material discovery, fabrication, and mass production of new materials. Because this topic is so broad, a basic research needs assessment process would help identify the highest priorities or largest opportunities (e.g., Should photocatalytic materials be a priority or not? What is an effective staging order for the application of computer-based material design?).

PHOTOLYTIC CONVERSION: Although direct conversion of CO_2 to products using energy from sunlight has obvious attractions, it needs low energy density per unit area and has large land area requirements, low yields, and difficult separations and harvesting of valuable products. Progress, especially to commercialization, will require new catalysts, substrates, reactors, and techno-economic assessments, suggesting a long-arc R&D effort.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

Lifecycle analyses are needed that incorporate socioeconomic dimensions of CO_2 conversion and utilization. Many important economic questions arise from the existence of CO_2U products; for example, the market viability of hydrocarbon fuels from CO_2 captured from the air would likely require a significant carbon price. Consumer behavior and attitudes toward CO_2U products are also unexplored, with no useful prior analogs, but consumer sentiment will be central to market adoption and valuation of CO_2-based products. The same is true for questions of social and economic justice in relation to such products; for example, research is needed around the value of place-based innovation in serving underserved communities, the consequences and value of reduced or increased pollution from new CO_2-based manufacturing, the potential impact on global or regional supply chains, and microeconomic impacts.

The regulatory questions surrounding standards, procurements, and potential consumer health impacts are also unexplored; research is needed to identify and resolve statutory and regulatory barriers. Lastly, there are unique policy levers available in this space to be explored (e.g., government procurement mandates) that have precedents in other high-tech and clean-tech industries. The need for scholarship and new approaches for these issues is immense and must be a priority for the new carbon economy.

ACCELERATED WEATHERING AND MINERAL CARBONATION

OVERVIEW AND KNOWLEDGE GAPS

Natural weathering of most rocks (e.g., silicates, carbonates, and oxides) binds CO_2 from the atmosphere but typically takes centuries or millennia (Chamberlin 1899; Raymo 1991). Accelerated weathering, however, can draw CO_2 from the air in hours to months, binding it permanently into mineral phases, including those used commercially (Seifritz 1990; Lackner et al. 1995; Chiang and Pan 2017). Rocks rich in iron, calcium, and magnesium—ultramafic rocks, as shown in Figure 8— commonly have fast kinetics. Through efforts focusing on those minerals or increasing reactive surface area, these rocks can be reacted in situ or ex situ with CO_2 to form carbonate rocks and minerals to lock away atmospheric CO_2 on the timescale needed in the new carbon economy (Kelemen et al. 2011).

A substantial amount of heat is released in accelerated weathering reactions, providing a novel pathway to geothermal energy or process heat (Kelemen and Matter 2008). In some experiments and natural examples, these positive feedbacks produce rapid and nearly complete conversion of CO_2 to carbonate minerals, releasing more heat per mole than combustion of methane (O’Connor et al. 2004; Chizmeshya et al. 2007; Gadikota et al. 2014; Falk and Kelemen 2015). In many cases, positive feedback mechanisms can make operation and heat recovery very cheap and effective

(Jamtveit et al. 2008; Rudge et al. 2010; Kelemen and Hirth 2012). This approach can therefore provide multiple benefits: new products, such as aggregate, heat and electricity, and permanent binding and removal of CO_2 from the air and oceans.

FIGURE 8. *Geological Sequestration Resources*

This national-scale figure maps ultramafic rock types, which typically consist primarily of olivine- and serpentine-rich rocks. These rock types are potentially suitable as source material for mineral CO_2 sequestration

(CREDIT: KREVOR ET AL., 2009)

TECHNICAL R&D PRIORITIES

Near-Term (1-3 years) R&D Priorities

MINE PROCESS MODIFICATION AND RETROFIT: One clear near-term opportunity for carbon mineralization is in base metal, diamond, and asbestos mines hosted in ultramafic rocks. For active mines, applied research should focus on how to modify existing operations to capture CO_2 and convert waste rock to carbonates. For inactive or closed mines, applied research should focus on how to source CO_2 through very low-cost operations. A census of existing mine tailings is needed to determine the real climate and economic potential for this application of accelerated mineralization. Lastly, new research is needed to investigate the possibility of mining ultramafic rock and creating tailings for the specific purpose of DAC and CO_2 storage through mineralization.

CO_2 GAS-TO-LIQUID TRANSFER: Current rates of carbon mineralization are limited by CO_2 flux across the gas-to-liquid reactive interface, and dramatic acceleration is achievable by enhancing the transfer of CO_2 from air to the fluid. Accelerated weathering and DAC need both novel CO_2 capture and transport methods with enhanced efficiency and advances in high surface area contactors.

MAPPING HIGH-VALUE PROJECT OPPORTUNITIES: Accelerated weathering opportunities are geographically limited by the supply of abundant metal oxide deposits (Sandalow et al. 2017; Krevor et al. 2009; Bodénan et al. 2014). In addition, point source CO_2 is preferred over atmospheric sources due to cost and process intensification, further limiting the geographical range. Therefore, an important first step is to map at a more granular level the co-occurrence of geological and nongeological potential feedstocks with CO_2 point sources. A regional "sweet spot" map will help focus the R&D community toward market opportunities and reveal site-specific locations for study.

Mid-Term (3-10 years) R&D Priorities

ASSESSMENT OF ANTHROPOGENIC FEEDSTOCKS: In addition to feedstocks of naturally occurring minerals, there are potentially human-made feedstocks, including steel slag, red mud from aluminum smelting, waste and reclaimed metal, and others that provide new opportunities in both waste remediation and production manufacturing (Bobicki et al. 2012). In some cases, mineralizing these human-made feedstocks with CO_2 will require additional processing, novel reactors, and a better understanding of fundamental chemistry to reach markets. In part, this may be related to additional environmental risks associated with their use (see below).

ENVIRONMENTAL TECHNICAL ASSESSMENTS: Accelerated weathering may involve substantial operations within diverse ecosystems (e.g., jungle, desert, arctic). While in some cases no additional mining or processing is needed, scale-up or other methodologies may affect biota, water resources, and land access in unexplored ways. Even those approaches with likely minimal surface impacts (e.g., in situ mineralization) could have impacts on groundwater resources. R&D is needed to understand what concerns are most important and releveant, and if there are straightforward operational or technical approaches that could mitigate or obviate risks or create benefits, such as the removal of harmful elements or compounds.

IMPROVED MINERAL KINETICS: Promising ways to expand potential markets and environmental benefits include the development of new forms of mineral treatment and comminution (e.g., with lasers or using waste heat), which will reveal new products, elucidate commercial opportunities, and expand the potential range of applications and total CO_2 removed or treated.

IN SITU MINERALIZATION EMULATING NATURAL SUBSURFACE PROCESSES: As noted, a potential inexpensive route to DAC and solid carbon storage, as observed in some natural systems, could utilize the circulation of surface water in permeable networks in subsurface ultramafic rock, followed by the production of carbon-depleted water at the surface to draw down atmospheric CO_2. Here, research should focus on reactive transport, including integrated hydrology, reactive chemistry, heat transfer, and fracture creation, with the goal of maximizing CO_2 removal and heat production while reducing capital and operating costs. While some of this may involve direct hydrofracture stimulation, in other cases autofracturing associated with stress realignment and mineral volume changes from with the injection or the reactions themselves may occur.

Long-Term (10-30 years) R&D Topics

EXPANDED ACCESS TO NEW ULTRAMAFIC SYSTEMS: Expanded implementation of accelerated weathering beyond the near-surface ultramafic geology (e.g. offshore) is a key initiative for the new carbon economy over the long haul. Exploratory research is needed to determine what fraction of the resource might serve as a reserve and how to exploit the mineral and heat resources in competitive markets through the application of advanced drilling, completion, and operation techniques.

EXPANDED VALUE FROM NEW MINERALIZATION: The economics and value of mineralization can be improved with additional revenues. For example, rare-earth elements, precious metals, and amorphous silica may be recovered from the alkaline brines brought to the surface by accelerated weathering. Research is needed to identify key opportunities and develop technologies and practices to exploit them, followed by optimization intensification of the approaches.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

Accelerated weathering invites a number of legal and social questions. For example, many of the most promising feedstocks, such as minerals with labile metal oxides and good kinetics, are classified and managed as dangerous wastes (e.g., asbestos). The regulation of these wastes may complicate and limit opportunities for CO_2 conversion to products, interfere with public acceptance, and affect market value. Similarly, the legal characterization of these novel subsurface resources may be poorly suited to existing statutes and approaches to obtaining mineral rights.

CROSS-CUTTING TOPICS AND TECHNOLOGIES

Naturally, many potential endeavors in the new carbon economy face common gaps and shared challenges. Some are social, economic, or political, and others are primarily technical. Each cross-cutting topic below represents a very large arena in which a concentrated effort by an active research community would accelerate the deployment to market of a range of diverse approaches to carbon removal and utilization.

LIFECYCLE ANALYSIS

Robust lifecycle analysis specific to direct air capture, products of carbon capture and utilization, and accelerated weatherization should receive targeted and dedicated support to improve data and methodologies. These will require the collection of data specific to each carbon removal approach, ideally shared in an open-source format through a new and active community of practitioners. Governments and key stakeholders (customers for lifecycle analyses) should also create national and international working groups to better share results and standardize their outputs, as a means to jumpstart the process of creating product standards.

IMPROVED ECONOMIC MODELS

Current global economic models used in climate planning and forecasting (for example, general equilibrium models) lack accurate representations of any of the engineered approaches discussed here. Models for the most commonly represented carbon removal approach—bioenergy with carbon capture and storage (see Chapter 5 on hybrid pathways)—broadly lack accuracy in feedbacks for water and land use, and all other engineering approaches critical for the new carbon economy are absent. This severely limits the ability of governments, investors, and other decision-makers to understand the value offered by these approaches. Developing accurate modules for DAC, accelerated weatherization, and CO_2U, and improved models for carbon capture and storage and bioenergy with carbon capture and storage, would cost very little and could be done very swiftly.

OTHER ADVANCED TECHNOLOGY

The dramatic advances taking place in other disciplines will unquestionably allow more innovation and accelerated progress in engineered approaches for the new carbon economy. New approaches to reducing costs, improving performance, and speeding scale-up of engineered carbon removal and utilization approaches will be enabled through additive manufacturing, discovery of new materials, use of big data and artificial intelligence, new gene editing techniques such as CRISPR, synthetic biology, and even the rise of cryptocurrencies and blockchain-enabled transactions. Importantly, these advances will also heighten new ethical, philosophical, social, political, and legal questions on their own, which may directly affect the deployment of any of these systems.

RESOURCES REQUIRED

A number of gaps in facilities, centers, and other technical infrastructure limit the rate and magnitude of progress toward the new carbon economy. The following topics represent key starting points for immediate discussion and support.

HUMAN CAPITAL

The wide deployment of engineered solutions will require a multidisciplinary approach, including material science and engineering; process engineering, reactor engineering, and system design; geoscience, notably geomechanics and geochemistry; chemical and mechanical engineering; and techno-economic and lifecycle analyses. New students and potential practitioners interested in applying their talents to the new carbon economy cannot enroll in interdiscinplinary programs specifically attuned to the new carbon economy, as the key topics remain spread across a multitude of departments, schools, and disciplines. Universities will need to create training programs and initiatives that are interdisciplinary and provide internship opportunities to give students opportunities to learn by doing. The three pathways discussed above, especially CO_2U, will evolve into enhanced disciplines (e.g., regenerative chemical engineering, CO_2 conversion chemistry) with their own professional societies. In tandem, social science experts and practitioners will need to quickly increase their familiarity with these technical areas and expand their research enterprises to address multiple facets of the new carbon economy. However, productive and effective communication among all of these disciplinary communities may not happen spontaneously, creating a valuable role for the New Carbon Economy Consortium to facilitate these unusually wide cross-disciplinary collaborations.

DATA INFRASTRUCTURE

Data exchanges: Data-sharing platforms and centers of excellence are beginning to emerge across a number of Consortium participant institutions. However, these platforms for collaborative research and knowledge sharing are insufficiently resourced to provide these services and need to improve and expand their data sharing and aggregation capabilities and standardization of process and results. As more data are created for more new carbon economy undertakings, federated and shared data volumes will help avoid waste, duplication, and slow growth. The needed data exchanges include:

- Libraries of new materials and their properties;
- Atlases for new manufacturing processes; and
- Geographic information system (GIS)–enabled data centers and platforms for opportunity mapping in the new carbon economy, similar to the U.S. DOE's Carbon Sequestration Atlas.

Standardization will prove essential. For example, consistent and comparable experimental designs and results (e.g., light sources, efficiency, quantum yield) should be planned or codified by practitioners together early on.

MODELING

Conventional economic modeling efforts commonly fail to incorporate or represent engineered solutions for the new carbon economy, such as economic equilibrium modeling or lifecycle techno-economic modeling. Even some active modeling approaches, such as quantum mechanical modeling for material discovery and design, are focused only rarely on new carbon economy problems. New and more sophisticated physical and chemical models must be developed and tested. For example, there is no broadly available modeling platform specific to DAC or the novel bespoke reactors for CO_2 conversion to fuels. Existing modeling platforms (e.g., ASPEN, MFiX, GEOS) require amendment and augmentation at a minimum, and new simulation and modeling platforms will be needed both for accelerated commercialization and human capital training. Universities and national labs that are part of the New Carbon Economy Consortium have the opportunity to support new platforms to share data and models. For large data volumes and complex process models, platforms of common interest should form and federate.

TESTBEDS

As technologies mature, the path to commercialization can be sped up by dedicated test facilities (e.g., the National Institute of Standards and Technology), which allow better development of standards and intercomparison of processes, technologies, and system characterization. Platforms to test carbon capture, utilization, measurement and verification, lifecycle analyses, and techno-economic comparison are all needed. These platforms should ideally be networked to test performance and efficacy of solutions, with results shared nationally and internationally. For CO_2 utilization, one testbed exists in Vancouver, and two additional testbeds are being built in Wyoming and Alberta. A testing center is also needed for cement and concrete performance to help develop industrial and commercial standards for their licensing and use.

RESEARCH NETWORKS

Targeted centers of excellence: Dedicated research centers are needed to spur technological breakthroughs and train large numbers of people with the skills and expertise on which the new carbon economy depends. Successful examples of publicly funded, targeted research centers include the Department of Energy's Energy Innovation Hubs and Energy Frontier Research Centers, the National Network for Manufacturing Innovation, Arizona State University's LightWorks, and various National Science Foundation programs. An important part of the work of the New Carbon Economy Consortium is to identify those centers that are most warranted. In some cases, existing centers can be expanded, while in others, fresh approaches will require new brick-and-mortar facilities.

U.S. federal funding agencies, such as the National Science Foundation, Department of Energy, National Aeronautics and Space Administration, Department of the Interior, and Department of Defense, have strong existing R&D programs and should identify gaps and limitations in their support of R&D related to the new carbon economy. Coordination among internal offices and across government could help avoid overlap, duplication, and waste. Based on these efforts, these agencies can consider additional funding lines within or adjacent to existing programs that would expand their scope to explore core research and development topics for the new carbon economy. Funding platforms in government or industry can ideally be long-lived in order to support scientists and practitioners and allow promising students to complete their work and training. Lawmakers can consider adding report language that helps identify important programs and outcomes as well as direct components of spending to those ends. Long-lived and stable funding will allow technical work to launch and complete foundational research tasks.

NEAR-TERM OPPORTUNITIES FOR PROGRESS

While each pathway above proposes short-term actions to further the knowledge enterprise necessary for the new carbon economy, there are additional actions that can be launched today:

- **DEDICATED WORKSHOPS:** There are no journals dedicated solely to carbon removal, and the body of knowledge for the new carbon economy is spread across academic disciplines and research labs. Although the number of publications and conferences on carbon removal and carbon-to-value is growing, more—and a more diverse set of—platforms are needed to engage professionals and thought leaders in the new carbon economy. Given the paucity of conferences dedicated to some topics in engineered solutions, targeted workshops are needed to develop the R&D agenda in detail. These workshops need to include both technical sessions on specific topics (e.g., accelerated mineralization) and nontechnical sessions that address the social (e.g., social justice), economic, political, and legal aspects. Reports from these workshops will serve as the basis for future R&D roadmaps and articulate specific findings and recommendations to potential R&D funding agencies and sponsors. These reports will be designed to directly engage industry, government, and academic experts in the field.
- **PILOT-BASED DATA EXCHANGE:** In many of the engineered areas discussed in this chapter, pilots are already underway. They provide site-specific economic and technical performance data, as well as lessons learned from the process of launching projects. The new carbon economy needs a data-sharing network for these pilots that can guide future training, modeling, economic assessment, and policy studies.
- **IMPROVED GLOBAL ECONOMIC MODELS:** Economic models do not currently serve engineered approaches well, but their enhancement can be done very quickly and at low cost. Improved models are needed for carbon capture and storage and bioenergy with carbon capture and storage (see Chapter 5). Accurate modules are also needed for DAC, accelerated weathering, and CO_2 utilization.
- **TESTBED FUNDING:** Using the multiple testbeds that are in operation or being configured, outcomes from pilot projects can be provided to the R&D community and potential investors. Dedicated funds are required to cover the costs of shipping new devices to these testbeds for testing, installation, operation, data recovery, data distillation, and reporting. This should be a high priority, and it will allow those researchers and practitioners with devices and approaches close to market to rapidly finalize designs.

Chapter 4: Biological Solutions

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INTRODUCTION

Biological systems, including aquatic, food, and agricultural systems, offer a range of opportunities for carbon removal and value creation, with the potential to be widely adopted across diverse regions and landscapes. Photosynthesis removes CO_2 from the atmosphere, which can then be sequestered as carbon in trees, other plants, and soils. Biological carbon removal approaches can also improve water quality, ecosystem resilience, biodiversity preservation, and crop yields, and these approaches hold the technical potential to remove between 4 and 12 Gt CO_2-eq annually through 2030 (UNEP 2017; Griscom et al. 2017). However, the degree to which these CO_2-storage pathways are effective depends on our ability to shift the socioeconomic and political conditions that influence the management of agricultural, forested, and grazing land. As a result, additional research can help clarify and improve estimates of carbon removal potential and assess the likelihood that the carbon sequestration resulting from these management changes will be permanent, as well as help better understand the social, economic, and political changes needed to build a new carbon economy in land management industries.

The largest opportunity today to remove and store CO_2 and create economic value is likely to be found in forests. Estimates of the global technical potential for additional carbon sequestration range from 2-6 Gt CO_2-eq per year by 2030 (IPCC AR5 2014; Smith et al. 2013) and beyond (Houghton and Nassikas 2017), to more than 10 Gt CO_2-eq per year in 2030 (Kindermann et al. 2008 Griscom et al. 2017). Restoring ecosystems, such as riparian areas, can sequester significant carbon in the soil while creating a number of other environmental and economic benefits. Agricultural operations also offer ample opportunities to improve soil carbon sequestration and bolster the resilience and productivity of agricultural systems through innovative crops, novel management practices, and the development of soil amendments that help stabilize carbon for long-term storage.

RELATED ROADMAPPING EFFORTS

The capacity of biological systems to capture and store carbon to address climate change is a topic that has received increasing attention, including in the scientific literature, in the upcoming National Academies of Science report, "Carbon Dioxide Removal and Reliable Sequestration," in multiple IPCC reports, and in the U.N.'s Sustainable Development Goals. This chapter does not aim to present a comprehensive review of the field but rather focuses on highlighting knowledge gaps and research activities that target overcoming barriers to widespread adoption of biological carbon removal solutions, emphasizing economic opportunities and additional potential value of carbon removal.

MOST PROMISING CARBON REMOVAL APPROACHES AND KEY RESEARCH NEEDS

RESTORATION AND FOREST MANAGEMENT

OVERVIEW AND KNOWLEDGE GAPS

The current carbon sink in forests is estimated to be 1 Gt C/year[1], with the potential to more than double the terrestrial forest sink by 2050 by stopping deforestation and improving forest management (Smith et al. 2014; Griscom et al. 2017; Houghton and Nassikas 2017; Pan et al. 2011). Together, afforestation/reforestation and avoided deforestation could remove as much as 13.7 Gt CO_2-eq per year globally, much of that at a modest cost (Sohngen 2009; Griscom et al. 2017) and with many co-benefits that include improved water quality, restoration of ecosystems, increased biodiversity, and job creation in the forestry sector (e.g., the National Center for Ecological Analysis and Synthesis' Science for Nature and People Partnership program). These co-benefits have economic and ecological value that can be incentivized in the new carbon economy.

Enhancing carbon removal in forests will require a combination of expanding forests, improving forest management, and quickly eliminating global deforestation, including expansion of agricultural lands into existing forest ecosystems (Carter et al. 2017; FAO State of the World's Forests 2016), actions that inherently rely on shifting the value of standing forests and all of the ecological and economic benefits they provide. Changes in management associated with carbon removal in forests will need to take into account country- and ecosystem-specific carbon costs (including the energy costs of planting and seedling production and the opportunity cost of expanding forests) and the intended forest management (including thinning, harvesting, and production of forest products). Accounting of sequestration by forests must take into consideration the expected carbon turnover rate, including the risk of reversals from natural and anthropogenic causes.

Forestry approaches to carbon removal are at a high level of knowledge and technical readiness today (Richards and Stokes 2004; Birdsey et al. 2006; Pan et al. 2011), but require changes in the management of land and water resources and more robust and cost-effective systems for tracking carbon fluxes. R&D is needed to build assessment tools and a robust monitoring and verification system for carbon quantification, as well as to bring down the cost of assessment and deployment.

[1] Kt = kilotonnes (103 tonnes)

GtC = gigatonnes of carbon (1 GtC = (109 tonnes C = 3.67 Gt carbon dioxide)

PgC = petagrams of carbon (1 PgC = 1 GtC)

TgC = teragrams of carbon (1 TgC = 1 MtC)

C - CO_2 Conversion Factor C/CO_2 = 1/3.67

ECOSYSTEM RESTORATION: WETLANDS AND RIPARIAN AREAS

OVERVIEW AND KNOWLEDGE GAPS

Peatlands, wetlands, and riparian areas hold promise for carbon storage. Between 44 percent and 71 percent of the world's terrestrial carbon pool is stored in peatlands, riparian ecosystems, and coastal wetlands (Zedler & Kercher 2005). Draining for agriculture, burning, peat harvesting, and urbanization has significantly decreased the total land area of global wetlands, including the loss of one-third of global wetlands by 2009 (Hu et al. 2017) and more than 40 million hectares of wetlands in agricultural areas of the US Midwest alone. Restoring and protecting wetlands has particularly high climate change mitigation potential because wetlands trap sediments and their associated carbon (McLeod et al. 2011). Some of the benefits of enhanced carbon storage in wetlands may be lost due to increased methane flux to the atmosphere (Hemes et al. 2018).

Research suggests that long-term carbon sequestration rates in wetlands range from 0.1 tons to 5 tons of carbon per hectare per year (Parish et al. 2008; Mitsch et al. 2012; Smith et al. 2008). Thus, even relatively small investments in ecosystem restoration could yield significant carbon and environmental co-benefits, including carbon removal and sequestration at fairly low costs, from $10- 100 per ton of CO_2 (Worrall et al. 2009; Griscom et al. 2017). A recent analysis found 2.7 Gt CO_2-eq per year could be sequestered or avoided, with 57 percent of this potential at a cost of $100 per ton CO_2, and 29 percent at a cost of $10 per ton of CO_2 (Griscom et al. 2017). Beyond carbon sequestration, wetlands can generate valuable and monetizable co-benefits such as improved water quality and prevention of biodiversity loss.

Buffer zones around streams and rivers sequester carbon; reforestation of buffer zones also reduces the degradation of banks, deposition of sediment, pollution from livestock, nutrient runoff, and risk of floods (Giese et al 2003). In North America, reforesting buffer areas around streams and rivers has been shown to increase carbon storage by upwards of 37 percent over a six-year period (Fortier et al. 2010) and sequester as much as 11 tons CO_2-eq per hectare per year (Tufekcioglu et al 2003).

TECHNICAL R&D PRIORITIES FOR MANAGING AND EXPANDING FORESTS AND ECOSYSTEM RESTORATION

Near-term research priorities for ecosystem restoration revolve around data acquisition via monitoring networks and field experiments, while mid-term priorities utilize the data to model outcomes and build scalable monitoring and verification systems that can inform land management decisions. Long-term research priorities focus on the development of new business models made possible by robust monitoring and verification, modeling, and research on species-specific carbon sequestration potential.

Near-Term (1-3 years) R&D Priorities

Near-term research priorities below are interlinked and largely address improving and scaling of carbon data collection, including the ground game and high-resolution remote sensing that bridges the gaps and addresses geographic variation.

DATA COLLECTION AND ANALYSIS: Data from monitoring and analysis platforms (Gibbs et al. 2007; Banskota et al. 2014; Orgiazzi et al. 2018) help shape our interdisciplinary understanding of how land management affects forest carbon dynamics and how to quickly and effectively scale forest carbon removal. Technological advances in aboveground and belowground monitoring tools that specifically target measurement precision and reliability (e.g., low-cost continually measuring in situ sensors and high-resolution LIDAR) can facilitate wider and quicker adoption and ensure that the information can be embedded in predictive models. These improvements not only help to quantify carbon uptake and storage, but when linked with high-resolution remote sensing (below), they can also improve the effectiveness of policymaking that prioritizes carbon storage.

HIGH-RESOLUTION REMOTE SENSING TOOLS FOR MONITORING AND VERIFICATION: Reforestation and riparian restoration can be inexpensive and effective ways of improving carbon sequestration, but to better quantify and monitor carbon stocks over time, affordable high-resolution remote sensing tools are needed. Integrating with traditional monitoring and verification techniques can enhance precision and reduce costs of estimates. In the United States, active remote sensing tools, such as LIDAR and synthetic aperture radar, could supplement the existing Forest Inventory and Analysis (FIA) Program and other existing satellite carbon and vegetation monitoring systems (Goetz et al. 2009) to improve the quality and reduce the costs of ground sampling (Goetz and Dubayah 2011), as envisioned for NASA's Global Ecosystem Dynamics Investigation (GEDI). Testing and streamlining the integration of these tools is a near-term research priority.

GEOGRAPHIC VARIATION: Forests' carbon sequestration potential varies across species and geographies. The field is ripe for a big data approach to elucidate the localized potential for carbon removal efforts (e.g., from species-specific quantification of carbon uptake to interdependencies among soil type, climate, and biological communities that control underground carbon storage). Given anticipated changes to future climate conditions, the reforestation efforts must be optimized with species combinations that perform best under a range of possible climate scenarios, ensuring that carbon sequestration through reforestation is durable.

FIRE RISK MITIGATION: Risks of wildfire must be assessed and managed to avoid losses of sequestration potential. An interdisciplinary research agenda here should combine forest and carbon cycle science with social science to inform policy design that addresses the consequences of long-term fire suppression and the risks of carbon losses when fires go from periodic to catastrophic.

Mid-Term (3-10 years) R&D Priorities

WETLAND RESTORATION AND IMPLICATIONS FOR GREENHOUSE GAS EMISSIONS: Wetlands can sequester CO_2 but emit other greenhouse gases, namely methane and nitrous oxide. The complete greenhouse gas balance of wetlands is therefore context dependent and requires careful consideration and optimization (Neubauer and Megonigal 2015). From a greenhouse gas perspective, not every wetland system that can be restored should be; the monitoring tools and data frameworks developed in the near term should be used to inform restoration and management practices that are optimized with greenhouse gas reductions and carbon uptake in mind. As wetland restoration becomes more widespread, restoration activities need to be informed by a network of field experiments across a wider range of climates and geographies, coupled with continuous monitoring and modeling, to understand how greenhouse gas dynamics vary among intact, disturbed, and restored wetlands (see below).

REDUCING THE COST AND IMPROVING ACCURACY OF MONITORING AND VERIFICATION METHODS: Research is needed to improve the cost-effectiveness and integration of methods for monitoring and quantifying carbon fluxes in the landscape—especially methods that improve the spatial, temporal, and quantitative precision of carbon sequestration estimates. That could include smaller sensors and instruments that can be embedded into small monitoring stations and mass produced to increase spatial extent of measurements (e.g., Arable). Measurement tools that are spectral or colorimetric are cheaper and more portable than today's standard instruments. Further R&D is needed to improve their precision and functionality (e.g., Quick Carbon).

DECISION SUPPORT TOOLS: Land managers—farmers, ranchers, foresters, and land resource managers—balance competing interests that pit carbon storage against other environmental and economic realities. Decision support tools rely on robust monitoring systems and good data, both of which are a near-term research priority. Making immediate use of improved data access and tools (Wang et al 2010; Colomb et al 2013; Feliciano et al 2017), resource managers will be able to explore new possibilities and outcomes for future management and make their operations more efficient and profitable. Current decision support systems can continue to be improved and expanded to combine carbon storage data with other factors, such as the economic realities of changing land management practices and the impacts on biodiversity and other ecosystem services, including water, soil, and air quality (Bagstad et al. 2013; Funk et al. 2014). The integration of social science research and analysis with carbon monitoring and economic feasibility studies can increase our understanding of the barriers to changing land management practices and help us to overcome them; research that helps monetize carbon storage with other environmental and economic benefits is especially needed (Capalbo et al. 2018). Since these decision tools rely on models, it is critically important that models are selected, calibrated, and validated for the specific ecosystems and practices being quantified (Tonitto et al. 2016, 2018).

ADAPTIVE AND PREDICTIVE MANAGEMENT: As with decision support tools, adaptive forest management relies on tractable data on the implementation of practices and their measured outcomes. The dual goals of optimizing carbon storage and limiting the loss of soil carbon can be met within such adaptive approaches, which utilize modeling to optimize for the best match between practices and carbon outcomes, informed by research that combines on-the-ground tests of different land management practices with high-precision carbon measurements. A similar approach can be used to best match tree species with climate and soil types, optimizing their growth and forest resilience (Stevens-Rumann et al. 2017).

Long-Term (10-30 years) R&D Topics

DEVELOPING ROBUST BUSINESS MODELS FOR CARBON STORAGE: New business models can be developed to streamline transaction costs and make use of new incentive structures for carbon. The development of new business models and market mechanisms that take into account carbon storage will be an ongoing effort but will begin to take shape and scale in the longer term. These business models can incorporate other monetizable co-benefits, including improved nutrient management, water quality improvements, sustained or enhanced biodiversity, and enhanced system resilience, such as a new model that pays for the service of reducing nitrogen pollution by planting perennial grass bioenergy feedstocks (Woodbury et al. 2018).

ENGINEERING BETTER TREES: Many resilient and rapidly growing tree cultivars are being used in the U.S. plantation forestry industry, and these trees can also be used in reforestation efforts to improve the pace and durability of carbon sequestration. Building on this large body of forestry knowledge and expertise, research should focus on optimizing growth on marginal lands to sequester carbon and produce feedstocks for bioenergy. Doing so will rely on the outcomes of near- and mid-term research efforts that select species and varieties with desired characteristics and match species with soil types and geographic locations, modeled against climate scenarios (e.g., climate envelope models), which is a task for mid- and long-term research.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

Carbon removal solutions require a mix of technical disciplines (e.g., biochemistry with soil science) and social science disciplines (e.g., economics, behavioral science, decision support tools). Traditionally, these disciplines have not been funded to work together, and differences across academic cultures further limit collaboration opportunities. In the new carbon economy, both technical and social science disciplines are needed to make rapid progress in developing solutions that are economically feasible and overcome challenges limiting their adoption. Land use decisions are made in a complex milieu of social, economic, and biophysical conditions, affected by both local conditions and interconnected global markets. Carbon sequestration, in addition to bringing other ecological benefits of reforestation, is not currently readily monetized by landowners. We need specific economic incentives for carbon removal and other benefits of forests—created through forward-looking policy—to understand how to trigger a meaningful response among private landowners (Melillo et al. Chapter 13 2014; Rabotyagov 2010; Mooney and Williams 2007). Changing land management practices and creating policies that support carbon storage in forests and riparian areas require teams of geographers, economists, anthropologists, and other social scientists to explore potential paths for realigning the relationships between people and the land, while avoiding unintended consequences.

Sustainable and scalable change will also require addressing issues of carbon accounting and governance while meeting multiple objectives. For instance, local shifts in forest management could ripple through regional economies and present challenges to the viability of local sawmills, potentially reducing the availability of traditional timber jobs. Efforts to promote carbon sequestration should also consider spillover effects (for example, by working with local sawmills to ensure their compatibility with larger-diameter products if forests transition to longer rotations). Similarly, to ensure local acceptance and political support, it will be critical to engage local labor markets and educational institutions to train a workforce with skills to meet the changing demands of the new carbon economy.

Fire management is going to be an increasingly important aspect of carbon management. Managed controlled burns (i.e., prescribed fire) to reduce fuel loads are more ecologically beneficial than mechanical thinning (North et al. 2015), particularly in remote locations, but the impact of prescribed burns on soil carbon sequestration has mixed results (Alcañiz et al. 2018). Moreover, within the contiguous U.S., wildfire risk can not be reduced without addressing increasing housing trends in the wildland-urban interface (Radeloff et al. 2018). Interdisciplinary research combined with heavy investment from land managers, policy makers, officials within local and state governments, and private sector real estate development will need to be pursued to produce real-world changes in fire risk mitigation and forest and associated soil carbon storage.

SOIL CARBON SEQUESTRATION IN AGRICULTURE

OVERVIEW AND KNOWLEDGE GAPS

Just over 40% of U.S. land is considered farmland (USDA Census of Agriculture 2012). Land management practices can help store 0.01-0.07 kg carbon per meter squared per year in soils (Smith et al. 2007; Chambers et al. 2016; Minasny et al. 2017). If applied across all managed agricultural lands in the United States, this scales to several gigatons of carbon per year in sequestration, which starts to replace approximately 75 gigatons of carbon lost in the top 1 meter of soil since the agricultural revolution (Sanderman et al. 2017). The sequestration potential varies across landscapes and management practices, but when optimized could be enough to offset all projected emissions from land use change and agriculture (Pugh et al. 2015; Harden et al. 2017).

Since more than 37 percent of the global terrestrial surface is under some form of agricultural management (World Bank 2017), reducing greenhouse gas emissions in agriculture and carbon storage costs present clear research opportunities for the New Carbon Economy Consortium. With 53 percent of U.S. lands under agricultural management, there is a significant opportunity in the United States (USDA ERS 2017). Croplands cover almost 160 million hectares that have the potential to sequester 360 Mt CO_2-eq per year (Lal et al. 1998; Chambers et al. 2016), and grazing across 336 million hectares of land across the United States has the additional potential to store 257 Mt CO_2-eq per year (Follett et al. 2001; Chambers et al. 2016). The combined total would offset 9.5 percent of annual U.S. emissions (U.S. Inventory).

The cultivation of land to grow food can degrade soils, primarily through erosion and the accelerated loss of soil organic matter. Conversely, increasing soil organic matter and soil carbon can increase crop yields (Oldfield et al. 2018), enhance soil water-holding capacity, and increase the availability of other soil nutrients, including nitrogen (Smith et al. 2015), thus lowering the need for external inputs such as chemical fertilizer and irrigation, which have financial costs and greenhouse gas implications. These outcomes represent substantial economic gain. A paradigm shift has taken hold in some places, where food production systems that degrade soils have transitioned to systems that build healthy soils. Such a shift can simultaneously enhance long-term food security and remove large quantities of carbon from the atmosphere. Though some tools and technologies could provide improved efficiency to spur transition, the adoption of many soil carbon sequestration practices in agriculture does not require new tools or technological breakthroughs. As with forests, agricultural solutions can be harnessed immediately with modest incentives and at relatively low cost compared to other carbon removal solutions (Griscom et al. 2017; Woodbury 2018).

Shifting farming and grazing practices to maintain or boost productivity while decreasing external inputs and increasing soil carbon storage offers a profitable and sustainable climate change mitigation strategy (Griscom et al 2017). The following agricultural practices are promising means of increasing soil carbon storage, providing a range of economic opportunities available widely to communities and regions across the United States and the globe.

TILLAGE PRACTICES

Conservation tillage, including low-till and no-till practices, minimizes soil disturbance, retains intact roots, and supports long-term carbon storage in soils. This is especially true in degraded soils and with the addition of organic matter to soils (West and Marland 2002). Carbon storage in conservation tillage systems can also be increased through the cultivation of deeply rooting crops that move captured carbon into deeper soil profiles where carbon is less vulnerable to decomposition and loss (Sokol et al. 2018). Although no-till practices are not new, targeted research is needed to better quantify variation in their carbon storage potential across soil types and climates, as well as interactions with other management practices.

CROPPING SYSTEMS

Perennialization: Perennial crops can play an important role in carbon removal efforts by replacing annual grains and helping to support no-till practices. Perennial crops maintain intact roots from year to year, with extensive rhizosphere networks that host robust and diverse microbial communities (Toensmeier 2017). The development of crops with deeper root systems, including perennial grains, can promote more carbon storage at depth, including when combined with conservation tillage as discussed above; deeper carbon pools are less vulnerable to disturbance and therefore more stable (Tiemann and Grandy 2015). In the United States, there is only one commercially available perennial grain on the market called Kernza (Tassel and Dehaan 2013). A targeted research agenda to develop more perennial grains for wide application is critically needed.

Cover crops and double cropping: Adding additional annual crops into a rotation can increase soil carbon and reduce greenhouse gas emissions. For example, cereal rye can be grown over winter and harvested as silage on a dairy farm. This practice has been shown to increase total forage yields by 17 percent to 51 percent in Pennsylvania, for example (Fouli et al. 2012). If a second harvestable crop is not feasible, another option is cover crops, planted into or after the main crop and usually dead before the next main crop is planted. Just as for double cropping, the cover crop provides continuous addition of soil carbon by maintaining root growth—which also builds up soil nutrients and bolsters agricultural system resilience by improving soil moisture, suppressing weeds, reducing soil erosion, and promoting healthy soils (Snapp et al. 2005; Fageria et al. 2005). While annual cover crops are widely used today, perennial cover crops are not, and their use would reduce or eliminate farmers' need to reseed the cover crop each year and would support other systems such as no-till, which also help sequester carbon. Double crops and cover crops are not a new invention, and they are widely planted in some parts of the United States, particularly the Midwest. A research agenda is needed that addresses the cultural and economic barriers to their wider deployment.

Crop rotation: Adding new crops to a monoculture or polyculture system has the potential to increase soil carbon by 3 percent to 4 percent, sequestering an average of 20 grams carbon per meter squared per year (West and Post 2002), with the net effect depending on soil type, climate, crop species, and management practice. However, specific species mixes need to be optimized to find the "sweet spot" where soil types, climate, and geographic locations maximize soil carbon benefits. There is an additional opportunity to develop hybrid mixes that are drought and disease resistant and add perennial crops into rotations.

GRAZING INNOVATION

The timing and intensity of grazing affects its soil sequestration potential and overall soil health (Conant and Paustian 2002; Conant 2010). While overgrazing negatively impacts soil carbon storage, livestock move frequently under holistic or rotational grazing practices, thus stimulating plant regrowth and trampling organic matter and manure into the soil (Jacobo et al 2006; Allen et al 2011), which can increase soil carbon when coupled with long rest periods (McSherry and Ritchie 2013). Studies of the efficacy of rotational grazing on soil carbon storage have shown promising results in some locations (Machmuller et al. 2015; Stanley et al. 2018). These results need to be verified by extensive fundamental and field research that addresses factors such as soil type and precipitation regime.

TECHNICAL R&D PRIORITIES

Near-Term (1-3 years) R&D Priorities

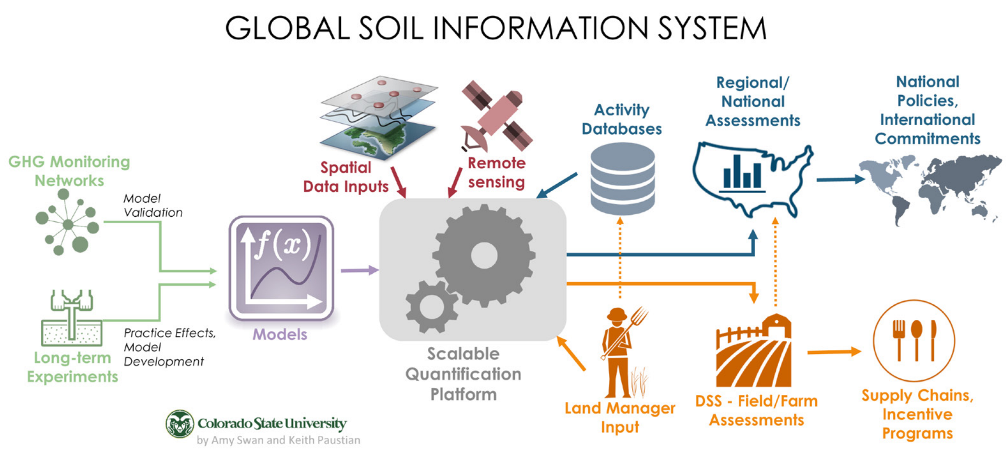
A small number of specific breakthroughs would help facilitate a rapid transition and scaling of soil carbon sequestration in agriculture. These breakthroughs involve advances in soil carbon science, improved monitoring and verification methods, and the integration of carbon accounting with on-the-farm planning tools and information management systems (e.g., carbon farm plan, COMET-Farm, farmOS) that take into account the economic aspects of the operation, policy support, and financial incentives.

SOIL CARBON SCIENCE: Current understanding of the effects of interactions between soil minerals and organic matter derived from both plants and soil fauna, including microbes and animals, on long-term soil carbon stabilization is limited and context dependent. We are also learning that processes that govern soil carbon transformation and stabilization are largely microbially driven (Schmidt et al. 2011; Cotrufo et al. 2013; Lehmann & Kleber 2015). Finally, most soil carbon research to date has focused on the top 20 centimeters of soil, which is the most biologically active soil layer. However, plant roots and their associated biological communities reach beyond the top 20 cm, where soil structure is largely intact and the vertical transport mechanisms and relative contribution of dissolved organic and inorganic forms of carbon remain largely unexplored.

FIGURE 9. *Global Soil Observatory and Information System*

Monitoring networks and long-term expirements can inform models to build scable quantification platforms that support policy and improve supply chains.

(CREDIT: KEITH PAUSTIAN AND AMY SWAN, COLORADO STATE UNIVERSITY).



An expanded foundational research agenda is needed to improve our mechanistic understanding of the potential influence of plant and root inputs and microbial carbon for soil carbon stabilization and sequestration—a research agenda that will continually evolve as we learn more. Soil organic carbon and other ecosystem carbon pools also change very slowly, and they need carefully planned repeat procedures at decadal timescales for accurate quantification or radiocarbon measurements coupled with models that give an integrated calculation of soil carbon age and turnover, all of which are analytic tools that are time intensive and expensive. In contrast, N_2O emissions are ephemeral, and significant labor or expensive automated equipment are required to accurately quantify total emissions over a single growing season (Ogle et al. 2014). Soil carbon and N_2O measures are not only linked, but also subject to spatial heterogeneity from the micro to the landscape scale.

Immediate steps in the soil carbon science research agenda include establishing a soil carbon monitoring platform to resolve the mechanisms of soil carbon stabilization across soil depth in sites that span soil types and climates. This is also an opportunity to engage citizen science efforts to test new soil carbon monitoring tools and expand the spatial extent of measurements.

RAPID SOIL CARBON ASSESSMENT: On- and in-the-ground tools, with increased precision, are needed to quickly and easily quantify, track, and verify soil carbon over time, focusing specifically on resolving spatial and temporal issues related to heterogeneity in soil carbon storage potential. The development of an inexpensive point-and-shoot tool to measure soil carbon can supplement and eventually replace the need for destructive soil sampling, which is expensive and not feasible to scale. Such tools are under development today (e.g., Quick Carbon), and in the next few years, improvements in functionality and calibration with well-established methods will be instrumental to scaling up their use and filling in data gaps related to the spatial heterogeneity of North American soil carbon stocks. We also need to develop new tests that predict the long-term stability of soil carbon, not just measure snapshot concentrations or net changes. Analyses of different forms of soil carbon stabilization exist today, but are time intensive and expensive, limiting their widespread use and adoption.

Combining remote sensing, geospatial data, including digital elevation models and land cover mapping, with systematic soil sampling surveys and low-cost analytical methods, such as mid-infrared spectroscopy, shows promise for multistate and national assessments of soil carbon (Ahmed et al. 2017). Such analyses can go beyond total soil carbon to quantify important types, such as pyrogenic carbon, which is important for assessing both potential losses and sequestration (Ahmed et al. 2017; Orgiazzi et al. 2018). Improved measurement, verification, and reporting are also needed to quantify the relatively small changes in shallow and deep soil carbon (organic and inorganic) and to map opportunities to increase soil carbon based on biological and physical factors. In grazing systems, assessments of the impacts of different grazing practices on soil organic matter are needed, as well as how they vary across soil types, topographic features, land use history, dominant plant species, and precipitation.

MICROBIAL AND MINERAL CARBONATE PRECIPITATION: Carbonate (limestone) in its various forms is one of the largest reservoirs of carbon on the planet (Archer 2010) and a stable carbon reservoir on timescales of hundreds, thousands, and even millions of years (Lackner 2002; Olajire 2013; Sanna 2014). Soils have the potential to store carbonate under certain land management practices (Lal 2004; Beerling et al. 2018) but require concerted research on factors that control soil carbonate formation, focusing on both abiotic and microbially driven processes that can accelerate carbonate formation (Castanier et al. 1999; Doetterl et al. 2018). Microbes have the potential to enhance carbonate formation by creating conditions favorable for the precipitation process (Okwadha and Li 2010; Okyay et al. 2016). This research should aim to assess the potential for carbon sequestration and be coupled with geologically formed soil carbonates in order to identify the conditions that stimulate carbonate formation in soils. Finally, the capacity for microbial carbonate precipitation to store carbon needs to be quantified to determine whether this is a meaningful climate change mitigation pathway.

PERENNIAL CROPS: There is only one commercially available perennial wheat crop in the United States and a few under development, but to transform agricultural production toward meeting both yield and carbon storage goals, the majority of crops need to be perennial. The first perennial wheat took 20 years to produce, highlighting the immediate need for expanded research into perennial grains and demonstration trials across the United States. In addition, perennial crops with deeper root systems can promote more carbon storage at depth, where carbon is more stable (Tiemann and Grandy 2015).

MAPPING OPPORTUNITIES WHERE AGRICULTURAL PRACTICES HAVE HIGHEST SOIL CARBON STORAGE POTENTIAL: In the near term, the magnitude of benefits from no-till agriculture, double crops, cover crops, perennial grains, and grazing innovation on soil carbon need to be quantified across different soil types, climates, and historical land use factors. Process-based soil carbon models are needed that allow identification of the most promising areas for increased storage. More data are needed on how grazing practices affect soil carbon and associated economics so that appropriate grazing practices can be promoted according to soil types, geographies, and climates. Specifically, it is critical to:

- Gather comprehensive data on how grazing is managed across the United States and create a comprehensive map of soil carbon storage potential that links to grazing practices;
- Assess and quantify the carbon benefits of double cropping and cover crop systems to target implementation to locations where this practice is most beneficial;
- Improve the linkage between on- and in-the-ground measurements with current remote sensing tools to reduce the cost and expand the coverage of soil carbon measurement and verification under grazing and farming practices; and
- Improve soil carbon modeling tools based on observable processes to allow rapid and cost-effective identification of areas and practices with the greatest potential for further carbon storage.

Mid-Term (3-10 years) R&D Priorities

Mid-term priorities rely on advances in soil science and a series of "sweet spot" analyses that can guide the development of new crop varieties that achieve duel goals of increasing yields and soil carbon storage while informing planning and policy design.

PLANNING TOOLS: Agricultural producers are managing for multiple outcomes, including profits, yields, nutrient inputs, water, soil health, and the long-term sustainability of their operations. Making decisions that optimize multiple factors requires good data and tools that bring those data together in a shared framework or tool. Agricultural producers need decision support tools that integrate soil measurements with geospatial information on soil type and climate, on-the-ground information on management practices, and the economic realities of their implementation. Good data are absolutely necessary and a research priority in the near term. In the mid-term, decision support tools that are developed can be integrated into a precision agriculture system that works at producer or operation scales to combine soil and plant measurements with optimization for productivity and soil carbon storage, doing so at a subfield scale with nonpropietary tools that link with agricultural testbeds and experiments.

ENGINEERED CROPS: The widespread deployment of multicropping systems will facilitate decreasing system inputs (e.g., fertilizers, herbicides, and pesticides that carry their own greenhouse gas emissions) and a transition to agricultural practices that maintain or increase productivity and bolster soil carbon storage. These crop types include engineered crops that help store carbon, such as crops with increased photosynthetic rates and deeper and more lignin-rich root systems, drought- and disease-resistant hybrids, and perennial grains and cover crops. This work should be guided by considerations of genetic, physiological, and ecological basis of plant adaptation, targeting desired traits such as drought adaptation, low soil fertility, and root development (Gage et al. 2017; Marshall-Colon et al. 2017; Bhosale et al. 2018).

DATA NETWORKS AND INTEGRATION: Improvements are needed in data richness, management, access, and connectivity across soil carbon monitoring networks. For these networks to be broadly useful, it will be necessary to implement common templates that capture relevant data streams and allow for global synthesis research. Opportunities to bolster current efforts include those spearheaded by the National Science Foundation's Critical Zone Observatory (CZO) soil carbon program and the National Ecological Observatory Network (NEON), with the goal of building out a soil observatory that can serve carbon removal efforts over the long term.

POLICY AND BUSINESS MODEL INNOVATION: Moving beyond a piecemeal approach that treats each agricultural challenge separately to comprehensive support will make producers' transition to carbon storage practices clearer and easier, especially if there is a way to monetize carbon storage as an ecosystem service. When producers implement practices that increase soil carbon storage, this changes a farm's costs, revenues, and the specific sources of profits (Antle and Mooney 2002). For producers to make the transition from conventional to more regenerative and soil carbon storing practices, they need business planning support (e.g., carbon farm planning) and a foundation of robust soil carbon science. In the case of carbon-farmed crops, markets and specific labels that identify carbon-farmed products may need to be developed and, as with any management change, producers will need to learn new production techniques and nuances of the new market.

- Land lease duration/structure: Current short-term land leases encourage an emphasis on short-term gain through practices that do not promote carbon storage. Policy research that develops incentives to support longer leases and a shift in lease structures will also allow for the build-up of carbon in soils and encourage practices that optimize carbon storage.

- Carbon-negative certification program: In biological systems, there are indirect and opportunity costs associated with promoting photosynthesis and soil health (including soil carbon storage), and the products created using carbon removal techniques have to compete with similar products and services derived from fossil fuels, which are typically less expensive. A carbon-negative certification program would rely on robust carbon monitoring and verification schemes (an R&D priority discussed above) and highlight the added value of carbon-negative products and services. The rollout of such a certification program requires social science and policy research to ensure that unintended consequences are adequately considered.

- Carbon incentive system: A system is also needed that allows producers of goods and services that need to reduce greenhouse gas emissions to monetize their carbon-negative products and the associated co-benefits. The underlying assumption is that many consumers would be willing to pay a surplus to ensure that the carbon emissions associated with products are paid for. Market incentives like this can facilitate producers' transition toward carbon sequestering practices more quickly and sustainably.

Long-Term (10-30 years) R&D Topics

DOMESTIC SOIL CARBON OBSERVATORY: Near- and mid-term research activities are necessary to build a U.S.-wide soil carbon observatory, relying on the development of soil carbon monitoring tools and resolving the mechanisms that control carbon stabilization in soils that must be represented in next-generation soil carbon models. This observatory can stand alone or be embedded into other existing U.S.-wide observatories, such as National Ecological Observatory Network, and leverage citizen science efforts that utilize newly developed, inexpensive means of measuring soil carbon.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

Shifting agricultural practices toward increased carbon storage brings the important co-benefits of building soil health, improving soil water availability, and enhancing the long-term sustainability of food production—all of which create economic value. Implementing soil carbon sequestration practices in agriculture will require addressing some socioeconomic tensions at the core of land management, including issues of ideological differences and commonly held perceptions that climate-forward practices are bad for the bottom line. Finding the balance between feeding a growing population and maintaining soil fertility and enhancing climate change mitigation today without increasing inputs or carbon emissions, deforestation, or the conversion of grasslands that already store carbon (Bommarco et al. 2013) offers great opportunities for carbon storage and improved yields. Finally, policy and social science research that addresses the needs to improve land tenure rights and associated access to credit, markets, governmental programs, and land leases will be needed to ensure all farmers are brought to the table (Meinzen-Dick et al. 2017).

Another key need is to ensure that beneficial removal of CO_2 from the atmosphere is long-lived and limits unintended consequences. Increasing and maintaining the permanence of soil carbon gains requires both the implementation of existing legal tools and the development of new ones. Existing legal frameworks include conservation easements that prevent conversion of intact grasslands, but conservation easements can also be customized to be compatible with adaptive management needs of agriculture. While farmers are open to economic and/or policy schemes that incentivize soil carbon storage, recent research in Indiana showed that farmers would prefer that carbon credits for switching to no-till agriculture be paid via existing governmental structures such as subsidies rather than market-based payments (Gramig and Widmar 2017). Exploring this and related topics can help decision-makers, investors, and market operators transition to the new carbon economy.

As an example, existing crop index insurance could be adapted to integrate carbon storage and provide a pathway to the governmental crop insurance programs favored by farmers. In the United States, crop insurance is currently a hybrid of private sector and government partnerships (Smith and Glauber, 2012), creating two streams of potential funding for soil carbon index insurance. The economic co-benefits of increasing carbon content in soils may allow for policy discounts, increase insurance market stability, and lower short-term and potentially long-term risk. The world's 80 largest insurers have pledged to address climate-related risks and opportunities (ShareAction 2018), and there is opportunity to build on that momentum to test and expand economic- and policy-driven soil carbon capture solutions.

Land managers will need incentive structures that encourage altering existing or adopting new land management practices in these directions. The economic viability of management practices that increase soil carbon varies spatially and is driven both by the biophysical potential of soils and economic conditions, including prices, policy incentives, and disincentives (Antle et al. 2003; Mooney et al. 2004; Kurkalova et al. 2003; Tang et al. 2016). In addition, social factors affect adoption and must be understood. For example, prioritizing increased grassland productivity and resilience in grazing systems by promoting soil carbon storage can help maintain livestock production in a more variable climate; however, across much of the western United States, soil carbon sequestration through grazing must be balanced with recreational activity and tourism (Roche et al 2015). Finally, a certification program would help shift the political dialogue by providing a means by which individuals can participate in climate change solutions through consumer choices and helping to educate the public about the economic opportunities associated with addressing climate change.

SOIL AMENDMENTS AND NUTRIENT MANAGEMENT

OVERVIEW AND KNOWLEDGE GAPS

MICROBIAL ECOSYSTEMS

Microbes drive most of the carbon transformation processes in soils; hence, in degraded or exposed soils with high mineral-binding capacity, soil amendments that work to enhance the production of microbial biomass and speed up microbial metabolism can also increase soil organic carbon for long-term storage (Zhou et al. 2012; Doetterl et al. 2018). Microbial carbon use efficiency—the proportion of carbon assimilated by microbes that is used for microbial biomass production vs. lost as respiration—determines how effective certain microbial communities are at transforming plant-dervied carbon into stabilized forms of soil carbon. The effects of microbial amendments on soil carbon storage are compounded when they promote plant growth through enhanced nutrient supply or other beneficial interaction. A more comprehensive understanding of the factors that control microbial community structure and function (including abiotic controls and the effects of soil invertebrates) and the influences of microbial interactions on biogeochemical processes in soils will help target microbially derived soil amendments and improve our ability to predict their impacts on soil carbon storage. Specifically, our knowledge of how microbes function in natural systems is quickly growing, but our ability to predict how microbial innoculants will persist and perform in complex soil microbiomes and variable environments must catch up to make microbial amendments tractable and predictable

COMPOST

Compost addition can stimulate soil carbon sequestration in degraded lands and, in some cases, beyond the carbon contained in the compost itself, constituting a promising carbon removal solution where compost is readily available (e.g., municipal composting programs) (Ryals et al. 2016; Owen et al. 2015). In degraded and marginal lands, compost improves soil aggregation, enhances microbial function, and provides slow-turnover carbon, especially when combined with biochar biosolids, manure, and mulch (see Chapter 5). Biosolids from human and livestock waste add nutrients back to the soil and promote microbial activity, which are both keys to stabilizing soil carbon. Compost used in combination with other plant-based soil amendments such as biochar (discussed in detail in Chapter 5) or wood litter can improve overall soil health and simultaneously increase crop yields (Agegnehu et al. 2017). Moreover, compost has an additional climate benefit when it replaces other methods of organic waste management. Landfills are essentially uncontrolled, very leaky anaerobic digesters that convert organic material into CO_2 and methane. Composting can not only prevent those greenhouse gas emissions but also displace emissions-intensive fertilizer. Research is needed on the extent to which compost additions maintain carbon sequestration or its potential to catalyze positive feedbacks, such as promoting microbial communities that help store more carbon or supporting plant communities that maintain productivity and continue sequestering carbon under variable climate conditions.

ALGAE

Photosynthetic algae take in atmospheric CO_2 and produce biomass that can be converted into complex organic compounds used to produce livestock feed, fuels, chemicals, and other products. Although typically considered an advanced biomass feedstock (discussed in Chapter 5), algae can be leveraged to improve agricultural resource efficiency and productivity and as a direct soil amendment. The use of algae in agricultural systems presents opportunities to couple nitrogen and carbon fixation, thereby reducing fertilizer demands and increasing soil carbon. In fact, nitrogen-fixing cyanobacteria, often associated with algae, can be a form of "living fertilizer" that continually injects bio-available nitrogen into the soil, potentially improving crop yields while reducing fertilizer application (Bhardwaj et al. 2014) and catalyzing soil carbon sequestration via microbial pathways (Muñoz-Rojas et al. 2018), contingent on soil characteristics and climate, as discussed elsewhere in this chapter. Other high-value uses of algae include nutraceuticals production and additives for animal feed.

TECHNICAL R&D PRIORITIES

To enable widespread use of soil amendments that increase soil carbon storage, near-term research priorities focus on the development of cost-effective approaches to measuring, verifying, and reporting carbon sequestration and the improvement of measurement and modeling capabilities. These advances will allow us to track small changes in shallow and deep soil carbon and properly incentivize and value agricultural and biological carbon storage.

Near-Term (1-3 years) R&D Priorities

ASSESSING THE IMPACTS OF SOIL AMENDMENTS ON AGRICULTURAL PRODUCTIVITY: To ensure that soil amendments deliver the desired effects on productivity and associated carbon storage, they will need to be coupled with systematic and comprehensive measurements across agricultural practices, soil types, and climates. Immediate opportunities to assess the impacts of soil amendments include integration with existing agricultural experiments at universities and other observatory efforts (e.g., the National Science Foundation's National Ecological Observatory Network and Long-Term Ecological Research Network) and setting up field trials on real agricultural operations, such as farms and ranches, to systematically address the interactions between agricultural practices, soil types, and climate. In addition to direct profits from increased agricultural production, soil amendments may decrease the need for outside inputs, save water, and provide other ecosystem services. These economic and environmental benefits can also be tested within the field trial framework.

MATCHING SOIL AMENDMENTS TO LOCAL CONDITIONS: To ensure that soil amendments optimize benefits without compromising other soil processes, soil amendments should be tested across a range of sites, conditions, and land management schemes. Based on the knowledge gained, advanced agricultural practices can be developed that best match amendments to local soil, microbiological, geomorphic, and water limitations. To avoid unintended consequences, such as soil organic matter decomposition and increased soil carbon emissions, a better mechanistic understanding is needed of the vulnerability of stored soil carbon associated with the addition of plant, invertebrate, and microbial biomass under various conditions. Lastly, given the considerable cost of compost application at a scale that allows meaningful carbon storage, the best opportunities for compost additions need to be identified, taking into account the variations in the soil carbon storage potential across soil types, agricultural practices, and climates.

SOIL CARBON MODELING: The effect of amendments on soil carbon dynamics, including long-term storage, must be adequately represented in process-based soil carbon models. This includes the effect of amendments on the stability and mineralization of existing soil carbon—the so-called priming effect—and the sequestration of nutrients and associated costs.

LIFECYCLE ANALYSES: As soil amendments' market share grows and becomes significant in the new carbon economy and supply chains work to optimize greenhouse gas benefits, thorough lifecycle analyses will need to account for both the direct emissions of producing and distributing amendments and their soil carbon storage potential. The science utilized in such analyses is currently in its early stages and needs to mature rapidly.

Mid-Term (3-10 years) R&D Priorities

BIOPROSPECTING FOR BETTER MICROBES: While the importance of microbes for efficient and productive agricultural systems is increasingly recognized, we are in the early days of managing and manipulating the microbiome (Wallenstein 2017). Microbe-rich organic ammendments have long been used to enhance overall soil health and nutrient cycling. For example, compost tea can enhance overall diversity and activity in some applications. Recent advancements in microbiome sciences have begun to elucidate the roles of specific groups of microbes in reducing disease pressure, stimulating plant growth, and in soil formation. These insights inform the development of next-generation microbial products with scientifically validated modes of action.

While earlier generations of microbial products sometimes increased plant productivity, their modes of action were poorly characterized. In contrast, modern biostimulants have specific targeted functionality often gleaned from genomic information. For example, Mammoth-P is a microbial amendment that stimulates the release of soil phosphorus and improves plant flowering. The improved effectiveness of modern microbial products has attracted significant venture capital and corporate investment. Desired attributes of soil microbial amendments that support soil carbon storage include high microbial carbon use efficiency, rapid turnover rates, and temperature-insensitive metabolism, which reduces the risk of microbial processes accelerating in response to warming and releasing more CO_2 from soils. Developing microbial amendments with the desired attributes will require a better mechanistic understanding of soil microbes' response to plant tissues of different quality, in different soil types, and under different climate conditions, and of the role of biotic interactions (Crowther et al. 2015). This information can then be placed within a predictive modeling framework (Trivedi et al. 2013) to assess the potential for climate feedbacks, such as unintended increases in soil carbon loss, and forecast the amount and reactivity of microbial carbon sequestered in soil (Bardgett et al. 2008). Finally, scaling the use of microbial amendments will require developing a business case that goes beyond yield and monetizes the multiple benefits they provide in soils, including soil carbon sequestration and other co-benefits.

COMPUTATIONAL SOIL SCIENCE FOCUSED ON CARBON AND YIELDS: Soil and microbiome science generate big data, which can be messy, especially when it is generated via crowdsourcing. Massive amounts of data on microbial community structure and function (Widder et al. 2016), plant carbon chemistry, and soil characteristics within a holistic modeling framework will allow us to optimize soil carbon storage across soil types and climates. Here, the power of computational science will be harnessed to demystify the "black box" of soil and engineer soil microbes and especially microbial communities to optimize soil carbon storage. Since farmers are reluctant to share data, we will need to create a database with well-designed data privacy mechanisms and flexibility to encompass big data that are variable. The database would also need to integrate existing datasets, such as the U.S. Department of Agriculture's Rapid Carbon Assessment, to reduce the impacts of variability.

BRINGING DOWN COSTS AND MAKING THE BUSINESS CASE: The existing R&D and business development opportunities for microbial engineering, compost, and other biosolids await the development of new business models and favorable market and consistent regulatory environments. For these soil amendments to be financially feasible, R&D efforts must bring down supply chain costs (e.g., production, transportation, application) to levels that are on par with today's alternatives or cheaper. Efforts to identify the sweet spot where soil amendment matches soil and crop type will need to consider the business and market environments so that increases in crop yields and soil carbon storage are monetized simultaneously.

SYSTEMS ANALYSIS: Production systems (e.g., cropping, livestock) and even the food systems can be optimized to provide food, feed, fiber, fuel, and climate benefits. For example, an estimated 30 percent to 40 percent of U.S. food is wasted (USDA 2018), representing a very large financial and greenhouse gas emissions cost to society. Yet there are opportunities to reduce food waste and greenhouse gas emissions while simultaneously recycling nutrients and creating soil amendments that can help store carbon in agricultural soils. Systems models can help pinpoint opportunities to increase productivity while meeting climate change mitigation goals. Such systems models will require new and improved data and biophysical and carbon-accounting models.

Long-Term (10-30 years) R&D Priorities

IDENTIFYING AND LIMITING UNINTENDED CONSEQUENCES: The addition of soil amendments that target one element (carbon) is likely to impact other soil nutrients (e.g., nitrogen) and potentially stimulate the release of other greenhouse gases. As the research agenda on soil amendments matures and agricultural and soil systems move into new equilibrium states, research will need to also address biogeochemical interactions and broader ecosystem consequences to ensure that methods to increase soil carbon do not inadvertently increase greenhouse gas emissions.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

Social sciences research and scholarship have an important role to play in several areas. First, the uncertainty among the public surrounding engineering biological systems creates legal and cultural barriers to widespread adoption for the purposes discussed here. This includes uncertaintly about the permanence of soil carbon storage, inconsistent regulations, and a lack of vetted information about how different soil amendments affect production systems. Second, from an economic standpoint, soil amendments designed specifically for soil carbon storage, including microbial amendments, do not currently have a market except where they also increase productivity—and even then, their adoption faces cultural barriers, including producers' lack of familiarity. There are opportunities to integrate across systems and multiply carbon benefits, requiring innovative management approaches and business models that can account for multiple layers of carbon benefits. For example, soil amendments that target soil carbon storage should be adopted in agricultural and forest management schemes and produce similar improvements in measurements, verification, and accounting, as well as innovative market and policy incentives. Social science research can help chart a path that strikes a balance among environmental and economic needs within various social and cultural contexts.

CROSS-CUTTING OPPORTUNITIES

LIFECYCLE ANALYSES

Lifecycle analyses' ability to identify and evaluate risks are limited by data constraints. Key areas of uncertainty include indirect vs. direct emissions and their impacts on policies, regulations, and carbon-crediting systems (Cherubini and Strømman 2011). Addressing these knowledge gaps and uncertainties is critical for both quantifying the carbon footprints of climate change mitigation solutions and quantitatively identifying opportunities to reduce carbon emissions or enhance carbon uptake. Lifecycle analyses can also provide valuable data for use in integrated assessment models and other models that help guide decisions about land use and resource allocation. This presents an opportunity for cross-cutting research with engineered solutions (Chapter 3), hybrid bio/engineered systems (Chapter 5), and all modeling efforts.

SYNTHETIC SCIENCE

Interdisciplinary collaboration and synthesis of data and information from diverse resources is the next frontier in science (Hampton and Parker 2011; Baron et al. 2017). Synthetic science encompasses data-sharing platforms, common experiments in different locations, best practices for how to facilitate interdisciplinary collaboration, metadata standards, and data science tools. Existing physical centers, such as the National Center for Ecological Analysis and Synthesis and the U.S. Geological Survey's Powell Center, should be expanded. New centers focused on carbon management should be launched, in collaboration with government agencies that are directing carbon management research programs and government-funded efforts, such as the National Science Foundation's National Ecological Observatory Network (NEON) and Long-Term Ecological Research Network (LTER). Synthetic science applies across all new carbon economy endeavors. The Consortium itself is a synthetic science center, home to cross-cutting research that combines different kinds of expertise to address the multidisciplinary challenge of biological carbon removal and the intersection points with engineered solutions (Chapters 3 and 5 of this innovation plan).

RESEARCH RESOURCES REQUIRED

To meet the research needs described here and bring these carbon removal solutions to scale, we need to develop the new carbon economy's human capital, support and build new and existing data infrastructure to enable rapid information sharing and model integration, and deploy testbed projects that enable platforms to test ideas, fail quickly, and continuously iterate.

HUMAN CAPITAL

The institutions in the New Carbon Economy Consortium have an important role to play in cultivating, training, and deploying the human capital necessary to build the new carbon economy. For biological solutions to be successful and scalable, interdisciplinary training of the next generation of scientists, business leaders, land managers, and policy leaders is foundational. Biological carbon uptake and storage relies on the central disciplines of biology, ecology, forestry, soil science, and social sciences to ensure that these approaches make economic sense in the communities where they are deployed. Training that brings those disciplines together will be central in the New Carbon Economy Consortium, and many efforts are already underway in sustainability science and education (e.g., the ANGLES network for graduate leadership in sustainability). Also needed are agronomy, engineering, macroeconomics (markets and policies), and techno-economic analyses (supply chain and plant design) to develop biological climate solutions that can work in current and future markets. Job training that targets these topics together will prepare the next generation of researchers and doers. Scaling biological solutions will require truly multidisciplinary efforts that are larger than the sum of their parts.

DATA INFRASTRUCTURE

To develop and scale biological solutions, we need new and better decision support tools, knowledge-sharing platforms, and databases that build on existing platforms, such as the U.S. Department of Agriculture's Economic Research Service (ERS) and NEON, but are more accessible and transparent. As we gather more data on carbon storage in biological systems, we need the infrastructure and means (e.g., databases and modeling tools) to share data and apply results quickly.

MODELING

To simultaneously meet multiple challenges and minimize unintended consequences, a systems analysis approach across all carbon removal solutions is critical. Systems analysis will require robust data inputs and models that can address uncertainties in soil carbon science and the biogeochemical and ecosystem consequences of implementing biological climate solutions at scale (Baatz et al. 2018). Modeling is key to bringing field observations into predictive frameworks that help agricultural producers, ranchers, and policymakers make land management decisions and use evidence-based metrics to implement new practices. As modeling frameworks become increasingly sophisticated, both conceptually and in their simulation capabilities, they are starting to present both site-based attributes, such as land management, and global-scale processes, including climate.

Building better models will require us to:

1. Focus on improving the data
    - A. Increase the available data on soil carbon dynamics and the impacts of different land management strategies across both space and time
    - B. Remedy the reality that current soil and ecosystem models are data-poor and currently rely on a few studies to make predictions for entire regions
    - C. Incorporate the role of soil erosion, lateral movement of soil carbon, and burial of soil carbon in the stabilization and reactivity of soil carbon
    - D. Consider challenges associated with spatial scale and mismatch between data collection and the scale at which models are useful
    - E. Fine-tune spatially resolved and depth-sensitive process models that predict soil carbon stability and content within the biogeochemistry context, given that carbon dynamics in soil are tightly coupled with those of the biota, nitrogen, phosphorus, and water

1. Consider how models represent measurable processes and can address nonlinear data inputs and find approaches that avoid amplifying uncertainty as we scale up
    - A. Model complex interactions and nonlinear systems behavior, including mechanistic and predictable understanding of the impact of various carbon amendments (e.g., agricultural residue, manure, biochar) on the stability of native soil carbon and soil biodiversity (e.g., belowground biological systems)
    - B. Account for feedbacks from climate change on biological carbon stocks (e.g., temperature increases speed up microbial metabolism and increase the rate of litter decomposition in soils, thus increasing soil respiration)

c. Integrate existing models with precision agriculture efforts; and

d. Consider natural and engineered carbon sequestration pathways together to form a more realistic representation of how these solutions are likely to be deployed.

3. Integrate social science at the start

a. Move beyond integrated assessment models to include how cultural and socioeconomic contexts influence real-world outcomes for carbon removal

b. Integrate policy and economic scenarios that reflect the realities of implementing biological carbon uptake and storage solutions

c. Help develop new business models that support the application of these solutions in various situations and scenarios

TESTBEDS

Temperature and soil moisture variations influence the stabilization of carbon for long-term storage, and spatial variability in soil types further influences soil carbon dynamics, making predicting and managing soil carbon storage capacity a challenge. Soil carbon can be vulnerable to perturbations in some locations but resistant in others, driven largely by interaction between soil minerals and organic matter and the relative influence of root inputs, microbial biomass, and other biota. Given the complexities and context dependencies of these interactions in soils, we need a spatially explicit understanding of the capacity of different soil types to store carbon under natural and managed conditions.

The New Carbon Economy Consortium has an opportunity to organize field testbeds across the United States to quantify the impacts of different management strategies and soil amendments across spatial and temporal scales, targeting:

- The roles of microbes and other soil biota in carbon transformation and long-term stabilization in soils (Lehmann and Kleber 2015).
- The capacity of different soil types and mineralogies, under natural and managed conditions, to store carbon.
- The potential for carbon storage beyond the top meter of soil.
- How other potential co-benefits vary with geography and interact with soil carbon storage.

Within the testbed framework, the impacts of conservation practices and soil amendments on soil carbon storage can be examined in a systematic way across a wide range of species, geography, soil types, and climate. Increasing the precision of these measurements of biomass carbon will help bolster future policy incentives to support future carbon payments. For forests, observatories that quantify and monitor aboveground and belowground biomass using remote sensing and ground-based methods should be launched, with the goal of testing these methods at sites that geographically span the Consortium. Increasing the precision of carbon measurements will reduce uncertainty and bolster policy incentives to support future carbon payments. Similar remote sensing and ground-based tools can be used in agriculture, where we will need to build robust allometric relationships that are validated with field tests or utilize weekly crop progress reports, such as those available from the USDA's National Agricultural Statistics Service (NASS), that link soil moisture and crop condition (Sun et al. 2017).

All testbed trials would need to be done alongside socioeconomic and behavioral science research that is designed to understand how key barriers to adoption evolve as biological carbon removal scales up and policies and markets are developed. This is especially important because many of the approaches recommended here are new or have never been done at large scales.

RESEARCH NETWORKS

Harmonization of the metrics, measures, sampling strategies, and data platforms required for the success of biological carbon removal solutions is essential, as is incorporating the complexities inherent in spatial heterogeneity in soil type, topography, hydrology, land use, and regional climate (Harden et al. 2017). These complexities play out over timescales relevant to the permanence of carbon storage and can influence the accuracy of climate models. Such a challenge requires global cooperation in measurement and monitoring of data and modeling platforms that will allow rapid synthesis, scaling, and projections (Harden et al. 2017). A network approach also helps identify key regional information gaps and ecosystems with maximum carbon accumulation potential with minimal trade-offs between storage and food production.

To develop a platform for sharing data and models, we need to:

- Fill data gaps and improve data management and access.
- Improve connectivity and data sharing across soil carbon monitoring networks. For example, the National Science Foundation Critical Zone Observatory's soil carbon program is working to link global Critical Zone Observatories with the Long-Term Ecological Research (LTER) program, which is funded by the U.S. National Science Foundation and U.S. Department of Agriculture.
- Create or adopt common templates that capture relevant data streams and promote global synthesis research.

NEAR-TERM OPPORTUNITIES FOR PROGRESS

The Consortium has several high-value opportunities to catalyze rapid progress toward filling research gaps and building out the research resources discussed here. A high priority is to get the large-scale soil sampling and monitoring efforts off the ground as quickly as possible. This large boots-on-the-ground effort can be coupled with developing a point-and-shoot tool to measure soil carbon and other nutrients, helping calibrate the tool with well-established methods and filling in data gaps related to the spatial heterogeneity of soil carbon stocks across North America. We also have the opportunity to harmonize methods and observatory design with other large efforts, such as Europe's LUCAS Soil (Land Use/Cover Area frame statistical Survey Soil) effort (Orgiazzi et al. 2018). An easy-to-use and cheap measurement tool will also bolster future measurement and verification needs for policy supports, including payments for carbon storage. And easy-to-use tools that integrate with smartphones can harness the power of numbers through large citizen science initiatives.

Chapter 5: Hybrid Biological and Engineered Solutions

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INTRODUCTION

In the new carbon economy, synthetic and applied biology has the potential to transform sustainable energy production and help mitigate climate change in the process. Biological systems can self-replicate and self-repair, and when integrated with engineered systems, they offer opportunities to produce new technologies and systems that are low cost and widely deployed (Adesina et al. 2017). But to make meaningful progress, applied biological solutions must scale, presenting a set of research challenges and opportunities for breakthrough discoveries and innovations in both biological and engineered carbon removal and utilization approaches.

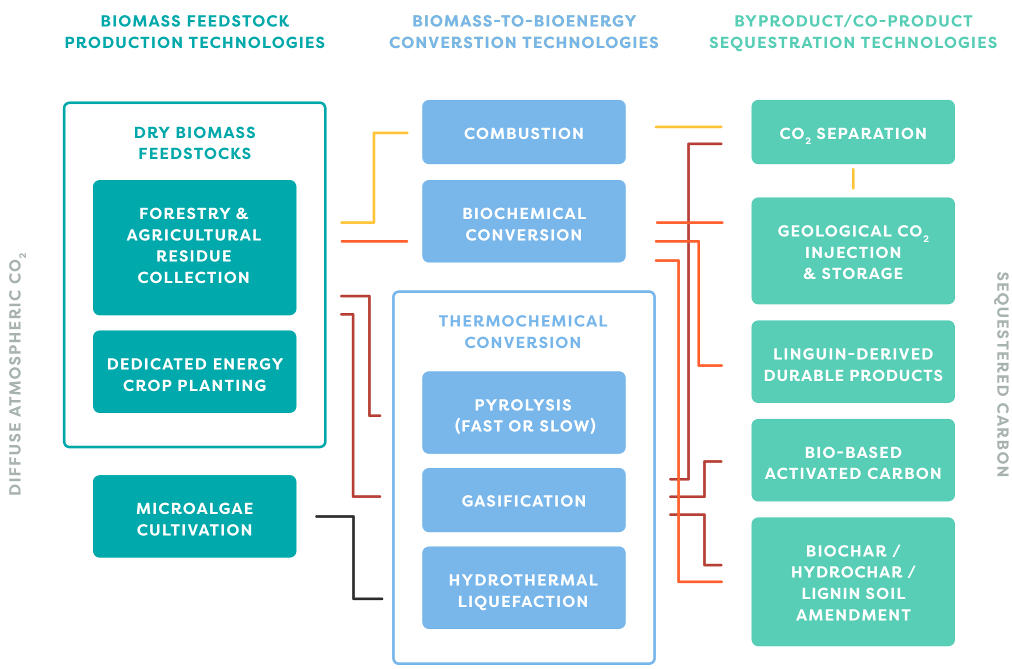
A number of systems that utilize both engineered and biological carbon removal solutions offer potential in the new carbon economy. In general, such hybrid systems involve the use of photosynthetic plants or algae to capture atmospheric CO_2 into their tissues, and the resulting biomass is used as a feedstock to create bioenergy, biochar, and products derived from aquatic and terrestrial algae. This chapter focuses on hybrid systems that provide energy, fuels, soil amendments, or services. A growing number of materials processes and technologies use biomass to manufacture durable goods, including engineered mass timber for use in multistory construction and plastics and concrete blended with biomass to reduce weight and improve mechanical properties (Robertson et al. 2012; Crawford and Cadorel 2017). To the extent that these products are long-lived, they represent a form of carbon sequestration. These products are largely outside the scope of this innovation plan, but provide exciting avenues for further research.

The term bioenergy denotes the conversion of biomass into energy or energy carriers, including electricity, heat, and solid, liquid, or gaseous fuels. Traditional biomass use—the combustion of wood or dung for cooking and heating—has been ubiquitous in human history. The last several decades have seen large-scale production of ethanol and biodiesel fuels from food crops, particularly in the U.S. (primarily from maize and soy) and Brazil (sugarcane). However, most decarbonization plans now envision wide scale-up of production of liquid transportation fuels and other modern energy products from nonconsumable cellulosic biomass feedstocks (Fulton et al. 2015). To the extent that energy extraction involves oxidation of part or all of the biomass carbon back to CO_2, modifications are necessary to ensure that bioenergy systems permanently store carbon. As highlighted in Fig. 10, such techniques include:

- Capturing some or all of the CO_2 generated during the conversion process and geologically sequestering it;
- Utilizing CO_2 generated during the conversion process (e.g., to grow algae);
- Partitioning a fraction of the biomass carbon into a long-lived solid product, such as biochar, which may be used as a long-lived soil amendment.

FIGURE 10. *Conceptual Diagram of Biomass Feedstocks, Conversion Pathways, and Potential Products*

(Credit: John Field, Colorado State University)



The sustainable use of biomass feedstocks to produce energy and related products is an important part of the path to a carbon-negative economy. This chapter brings together promising engineered and biological approaches that remove carbon from the atmosphere, which are or can be economically viable through targeted and visionary research and appropriate policy actions.

RELATED ROADMAPPING EFFORTS

The treatment of bioenergy in this chapter is different from existing bioenergy R&D roadmaps in that it considers breakthrough opportunities in bioenergy systems and the bioeconomy as tools for carbon management. Existing bioenergy roadmaps focus more narrowly on the specific challenges of making bioenergy products economically viable without consideration for the additional potential value of carbon removal. In fact, given the potential for realizing significant carbon-negative pathways via hybrid biological and engineered systems, it is critical to consider the carbon management opportunities in bioenergy and biofuel systems.

MOST PROMISING CARBON REMOVAL APPROACHES AND KEY RESEARCH NEEDS

TERRESTRIAL BIOENERGY

OVERVIEW AND KNOWLEDGE GAPS

For terrestrial bioenergy systems to be carbon neutral or negative, research opportunities generally fit into three broad categories: 1) lowest-impact sources of biomass feedstocks, 2) how those feedstocks are processed and converted to energy products, co-products, and byproducts, and 3) how co-products and byproducts can be managed to keep the carbon contained therein from returning to the atmosphere (Fig. 10).

1. SUSTAINABLY SOURCING TERRESTRIAL FEEDSTOCKS

A number of fundamental research questions, scaling considerations, and sustainability challenges are associated with bioenergy (National Research Council 2015). For bioenergy conversion technologies and biochar production processes that rely on dry cellulosic biomass as a feedstock, the sustainable production of such feedstocks is a key prerequisite to achieving net climate change mitigation in any carbon-negative bioenergy with carbon capture and storage (BECCS) scheme (U.S. Department of Energy). While early assessments of biofuel and bioenergy technology often treated plant-based feedstocks as carbon neutral (Searchinger et al. 2009), it is now well-recognized that the climate benefits of carbon-sequestering bioenergy systems can be offset or even eliminated if:

- Feedstock production causes persistent reductions in ecosystem carbon storage (Fargione et al. 2008; Liska et al. 2014);
- There are large emissions of nitrous oxide (e.g., biogenic emissions) at the production site (Crutzen et al. 2008);
- Productive land uses are displaced and lead to compensatory agricultural expansion into native ecosystems elsewhere (Searchinger et al. 2008).

Potentially the most complex and important aspect of bioenergy utilization is understanding and optimizing the economic, ecosystem, and agronomic prerogatives associated with biomass harvesting. The interplay between biomass harvesting and soil quality is particularly important: Better soil means more productivity for both food and energy. Using bioenergy approaches that improve rather than degrade soil quality is critical. Other critical sustainability considerations for bioenergy systems' effects on soil health and land use pertain to sourcing of biomass feedstocks. Large-scale estimates of biomass production technical potential now prioritize more sustainable biomass sources (Perlack & Stokes 2011), which include:

- The use of agricultural residues and municipal wastes that do not require land use change;
- Targeting dedicated energy crop cultivation on lands with minimal value for conventional agriculture, while producing ecosystem co-benefits (Robertson et al. 2008; Tilman et al. 2009);
- The use of aquatic and terrestrial algae where appropriate and feasible.

It is important to note that the removal of agricultural residues can in some instances reduce soil carbon sequestration potential or even lead to soil carbon losses, depending on whether complementary conservation practices are adopted (Kim et al. 2017). For example, crop and woody biomass residues are not simply classified as "waste"; rather, they have vital ecological roles in agricultural and forest ecosystems, such as residue decomposition recycling nutrients back to the soil and the build-up of soil organic matter. The unconstrained harvesting of crop residues causes soil degradation and ultimately reduces productivity. The adverse effects of biomass harvesting on soil quality can be partially mitigated by conservation practices such as no-till farming, cover crops, crop rotations that include perennials, perennial crops, and limiting residue harvest (see Chapter 4 on biological solutions).

FIGURE 11. *Challenges Associated with Bioenergy Production*

Estimates for bioenergy potential are highly variable and can range from 50 EJ/year to more than 1,200 EJ/year (Slade et al. 2014), but these will be limited by the availability of land for biomass cultivation and the need to transport biomass to processing facilities (Fuss et al. 2018). In the higher estimates of energy from bioenergy, about 80-100 EJ/year will be derived from agriculture and forest byproducts in 2050, with the remaining 180-300 EJ/year coming from dedicated energy crops that require land, water, and nutrients. Bioenergy crop production at this scale requires extensive land area. One hundred EJ/year may require up to 500 million hectares of land; for comparision, 1,600 million hectares globally are currently planted with agricultural crops, and 3,400 million hectares are used for pasture (FAO 2010). Global food demands are also projected to nearly double over the next 50 years (Tilman et al. 2001), and in the absence of dramatic yield increases or dietary changes, food production will be in direct competition with some forms of bioenergy. Additional barriers for bioenergy deployment and some proposed solutions are described in the table below, with darker rows highlighting barriers that are very difficult to overcome and lighter rows indicating barriers that are easier to overcome (based on Youngs et al. 2013).

BARRIER	EXAMPLE	PROPOSED SOLUTION
MARKET UNCERTAINTY AND RISK	Large capital investment for bioenergy with carbon capture and storage systems; economic uncertainty for planting and growing of dedicated bioenergy feedstocks	Incentives for new feedstock development, government insurance, and financial support (e.g., loan guarantees)
LAND FOR BIOENERGY CROP PRODUCTION	Conflict between crops for food vs. energy; ecosystem impacts	Agricultural intensification on existing land; environmental impacts assessments; utilization of marginal land for bioenergy crops
WATER AVAILABILITY	Conflict between water use for food production vs. energy crops; increased water shortages with changing climate	Water reuse and reclamation; development of drought-resistant bioenergy crops
BIOMASS AVAILABILITY AND YIELD	Competition with other biomass uses, such as fiber and building materials; production of high biomass crops	Incentives for renewable and sustainably grown biomass for bioenergy; improved agronomic practices and development of higher-yielding crops
SOIL NUTRIENT AVAILABILITY	High inputs of synthetic fertilizers (e.g., nitrogen and phosphorus) with high carbon emissions and leaching with overuse	Development and deployment of bioenergy crops with high nutrient-use efficiencies; use of precision agriculture methods for fertilizer delivery; recycling of nutrients from biomass processing facilities
BIOMASS TRANSPORTATION, DISTRIBUTED RESOURCES	Biomass resources in rural areas are not well-connected to high-use areas (e.g., urban consumers)	Investment in infrastructure; distributed processing and conversion plants; higher efficiency transport methods

(CREDIT: "CALIFORNIA'S ENERGY FUTURE, THE POTENTIAL FOR BIOFUELS," A REPORT FROM THE CALIFORNIA COUNCIL ON SCIENCE AND TECHNOLOGY, MAY 2013.)

Bioenergy systems configured for negative emissions (e.g., carbon sequestration via carbon capture and storage (CCS) or biochar co-production) face these same fundamental feedstock sustainability constraints. In light of the sustainable bioenergy feedstock sourcing challenges, there are opportunities to cultivate dedicated energy crops on low-value lands as a climate change mitigation strategy.

Indirect land use effects are an important consideration for any carbon-negative bioenergy system, as it must avoid causing increased CO_2 emissions that diminish the positive effects of the carbon removal achieved. For example, the indirect land use effects from the use of corn to produce ethanol increases global demand for grain, which can result in agricultural extensification and large associated CO_2 emissions from the loss of soil organic matter and standing biomass on the converted lands. While such leakage effects are notoriously difficult to estimate and their magnitude and robustness often contested (Zilberman 2017), it is important to include them at some level in lifecycle analyses of new bioenergy production systems' net climate impacts, and to consider them when attempting to minimize conflicts with conventional agriculture more broadly.

2. BIOMASS CONVERSION

A wide range of conversion technologies have been developed or proposed to produce biomass energy, products, and services. As noted in Fig. 10, certain conversion technologies are more appropriate for certain feedstocks and require additional processing to sequester carbon, including co-product and byproduct management. There is a distinction between simple combustion and more complex biochemical or thermochemical conversion that determines subsequent steps necessary to create products, including liquid transportation fuels. Biochemical pathways rely on living microorganisms, often yeast or bacteria, to process biomass into more useful forms. Much research and engineering has focused on the biochemical conversion of cellulose to fuels (Lynd 2017), and most of the pioneering commercial-scale cellulosic biofuel production facilities built to date are based on fermentation (Lynd et al. 2017).

While technical and policy barriers prevent wide production of cellulosic biofuels today, fermentation remains a key technology both in current biofuel production and in production of carbon-negative fuels. For instance, fermentation produces a pure stream of CO_2 available for carbon sequestration or utilization (Sanchez et al. 2018) using existing first-generation corn ethanol facilities with CCS. CCS can similarly be applied to cellulosic biomass fermentation to produce carbon-negative fuels at larger scales and potentially with a reduced environmental footprint.

In contrast, thermochemical conversion involves the controlled heating and decomposition of biomass into liquid, gaseous, and solid byproducts, and it often upgrades liquid and gaseous intermediates into finished liquid transportation fuels (Tanger et al. 2013). While thermochemical conversion technologies, including gasification and pyrolysis, have not yet achieved the same deployment scale as biochemical technologies, they are highly amenable to carbon-negative configurations, and thus are prime canditiates for additional targeted research and deployment support. Gasification is an autothermal process where biomass is partially combusted in an oxygen-restricted environment, producing a hydrogen- and carbon monoxide-rich synthesis gas ("syngas") product. Syngas can then be burned to produce electricity or catalytically upgraded to liquid fuels. Unlike gasification, pyrolysis involves controlled heating of biomass in an oxygen-limited or oxygen-free environment, and the temperature and ramp rate can be adjusted to favor liquid or solid products. Fast pyrolysis is optimized for the former, producing a range of liquid fractions including 1) a biocrude that, once stabilized by hydrogenation, can be refined into liquid transportation fuels or other products in existing petroleum refineries, 2) an anhydrosugar that can be fermented to produce ethanol, biobutanol, and other products, and 3) an aqueous fraction that can be used to produce low-grade fuels, acetate and road salt (Elliot and Neuenschwander 1997; Lian et al. 2010; Gayubo et al. 2004). Slow pyrolysis optimizes production of a solid carbon-rich fraction (see biochar section below).

Hydrothermal solvent liquefaction is amenable to wet feedstocks such as wet biomass, microalgae, sewage, sludge, and liquid manure slurries. The process involves heating biomass under pressure in the presence of a solvent to produce various liquid biofuel and hydrochar co-products. Both the yield and quality of the liquid bioenergy products are influenced by biomass feedstock properties and the operating conditions, including temperature, pressure, residence time, heating rate, feedstock particle size, and solvent properties (Gollakota et al. 2017). Feedstocks rich in lipids, such as algae, produce high-quality bio-oils easily converted to liquid fuels. Such liquid feedstocks are conservatively estimated to be more than 100 million dry tons per year in the United States (Drennan 2015), and industrial-scale carbon capture and utilization (CCU) production of microalgae will further increase the potential supply of wet biomass feedstock. Solvent liquefaction uses the same feedstocks as anaerobic digestion systems, but this emerging technology, though more expensive, has the potential to produce high-value liquid transportation fuels.

Biomass typically contains a higher ratio of oxygen to carbon than fossil fuels such as coal. As a result, biofuel production typically requires the addition of hydrogen or inefficient conversion of carbon in biomass to biofuels. Understanding the carbon conversion efficiency and sustainability of hydrogen production are key to understanding the lifecycle impacts of biofuels derived from both biochemical and thermochemical pathways.

3. CARBON CAPTURE, STORAGE, AND UTILIZATION IN BIOENERGY SYSTEMS

A key way of transforming bioenergy produced with a small greenhouse gas signature into net carbon-negative bioenergy is to capture, transport, and geologically sequester CO_2 from bioenergy production plants. The IPCC's Fifth Assessment Report (2014) noted the importance of utility-scale biomass combustion for electricity coupled with carbon capture and storage as necessary to avoid global warming beyond the 2°C threshold by the end of the century.

Traditional BECCS is large scale. However, the viability of large-scale BECCS systems for power generation is questionable. Utilities are quickly transitioning to renewable energy, namely solar and wind in the United States, and utility-scale BECCS for power generation may not be competitive. Existing markets can support low-carbon and carbon-negative transportation fuels, in contrast to power-sector application (Sanchez et al. 2018). For instance, the California Low Carbon Fuel Standard has proposed to include CCS and CCU in the carbon footprint for biofuels, providing relatively large incentives for CCS on biofuels.

A rigorous R&D program is crucial to understand how to capture CO_2 from distributed biofuel production facilities, leveraging research on coal-fired power carbon capture and sequestration. Two key knowledge gaps related to CCS need to be addressed to advance the new carbon economy. First, CCS must be evaluated in the context of a distributed bioenergy production industry. Key engineering and societal questions must be answered before we build systems to accumulate CO_2 from many distributed small sources: Do we attempt to use it on site or collect it into a network of pipelines and move it to geological sequestration sites? Second, it is essential to evaluate the relative competitiveness of different carbon capture strategies (Woolf et al. 2016)—CCS, CCU, long-lived products, and biochar systems—across scales, carbon price scenarios, geographic regions, and policy scenarios.

BEST PRACTICES

Several principles highlight best practices that should guide the New Carbon Economy Consortium's work in sustainable hybrid biological and engineered systems:

- Biomass needs to be converted to products or energy in efficient processes that minimize or eliminate CO_2 emissions. Capture and utilization or storage of CO_2 from bioprocessing plants will need to be efficient, favoring high-concentration CO_2 sources with on-site utilization or local storage.
- Carbon-negative performance of bioenergy systems requires process heat with zero-carbon emissions.
- Biomass must be efficiently collected and transformed into valuable precursors, such as bio-oil, as close to the source as possible to reduce transportation costs and emissions.
- Bioenergy systems should utilize diverse sources of biomass since the quantity, quality, and types of locally available biomass feedstocks vary from year to year and location to location.

- Converting biomass directly to liquid transportation fuels is likely to be more energy efficient than using electricity to produce synthetic liquid fuels from CO_2. As aircraft, agriculture equipment, and heavy vehicles are difficult to electrify, there will be a continuing need for high energy-density liquid transportation fuels—a need that bioenergy systems are well positioned to satisfy.

TECHNICAL R&D PRIORITIES

Near-Term (1-3 years) R&D Priorities

DEVELOPMENT OF DISTRIBUTED BECCS PROTOTYPES FOR ALL ENERGY PRODUCTS: To date, most CCS and CCU research has focused on large utility-scale facilities, which offer significant economies of scale but are likely not cost-effective for the diversity and dispersed nature of biomass resources and carbon storage opportunities. A more distributed model, employing a range of feedstocks, is likely to be less capital intensive and help BECCS scale sustainably. Research should focus on developing modular systems for BECCS (in more detail below) and address cost-benefit analysis and the social, societal, and policy limitations and opportunities for distributed CCS, CCU, and biochar systems.

MODULARIZATION: The use of modular bioenergy systems greatly reduces the capital needed to build a plant and increases the rate and extent of deployment. Advanced manufacturing methods, including additive manufacturing, can be used to build modular units and gasifiers, including new syngas, fermentation, and bioreactor systems. Shifting processes to lower temperatures can facilitate the use of other materials, including plastics instead of metals, and be amenable to 3D printing techniques that can lower the cost of production further. In addition to building modular systems small enough for mass production and transport by truck, it is critical to develop system controls that can integrate with modular systems. Optimizing system configuration can be achieved with simulations, and platforms must continue to evolve to represent the variability of feedstocks and potential system designs. Many of the advances in modularization for bioenergy translate to other uses, such as those described in Chapter 3.

Modular systems can be immediately used for new gas fermentation, and catalytic upgrading processes, using either syngas or CO_2, can be amenable to distributed small- and medium-scale plants (e.g., LanzaTech produces liquid transportation fuels using bioreactors filled with engineered microorganisms that metabolize syngas). New catalytic approaches to convert syngas directly into diesel range hydrocarbons with low separation costs are a priority, as are improved functionalization of catalysts (e.g., Greyrock, Velocys' Red Rock Biofuels and Bayou Fuels).

BIOENERGY FEEDSTOCK DEVELOPMENT: There is a rich body of research and development at U.S. national labs and private companies to address biomass feedstock variation, quality, and ease of utilization for conversion technologies; the dependence of many feedstocks on external inputs, such as water and fertilizer; and the lack of standardization among bioenergy systems (U.S. Department of Energy's "2016 Billion-Ton Report"). Building on the successes of these research programs, the development of dedicated perennial bioenergy crops, coupled with better soil management approaches and deep-rooted cultivars, could provide sustainable bioenergy feedstocks while simultaneously increasing long-term stable soil carbon stocks deep within the soil profile (Kell 2012). Specifically, plant genomics research should target biomass feedstock sustainability traits, and microbial genomics and better resolution of plant-microbe-soil interactions are needed to increase plant productivity and sustainability of feedstock sourcing.

Advanced genetic tools (e.g., CRISPR) can be applied to the development of new biomass stocks and hybrids that can grow across a wider range of locations. For example, bioenergy crops can be developed to grow in salty soils or provide more than one ecosystem service, such as supplying energy and bioremediating polluted soils simultaneously. Selective breeding can also target specific attributes, such as nitrogen fixation, drought tolerance, the need for external inputs, deeper roots and higher root biomass, enhanced soil carbon storage during growth, and higher photosynthetic capacity for perennial bioenergy crops (Ducat et al. 2012), among other co-benefits.

BIOENERGY FEEDSTOCK FIELD TRIALS: The development of new feedstocks, coupled with a network of field trials across sites with soil and climate variation, helps to ensure they can be produced sustainably and optimally matched to conversion opportunity. Field trials can be co-located with existing conversion infrastructure.

'SWEET SPOT' ANALYSIS: Systems analyses can also help optimize and identify "sweet spots" for facility co-location with distributed resources and variation in resource type. Regional clusters of biomass production can provide platforms to co-locate and co-transport CO_2 to favorable utilization options and permanent storage, thus maximizing the benefits of carbon sequestration.

BIOMASS GASIFICATION TO FUELS: Producing chemicals or fuel from biomass gasification tends to be constrained by bioprocessing capacity, and the process to convert syngas to liquid fuel products (i.e., Fischer-Tropsch reformation) creates intermediate byproducts that involve expensive separation and purification, requiring additional infrastructure and processing capacity. These issues can be addressed with a targeted research agenda. The development and deployment of smaller-scale and fuel-flexible gasifiers can help overcome issues of scale and capacity. Co-conversion of biomass with fossil fuel feedstocks, including coal and natural gas, should also be given a greater research emphasis as a necessary transition to biomass feedstocks and to learn by doing. Finally, small-scale gasification units can also produce long-lived carbon products such as biochar, providing additional revenue sources as biochar market opportunities grow.

BIOGENIC EMISSIONS ASSESSMENT: Assessment of biogenic emissions (i.e., changes in ecosystem carbon storage and nitrous oxide emissions) from biomass feedstock sourcing is particularly data-poor and requires the development of widespread and continuous measurement platforms that provide reliable and verifiable emissions data, building on existing databases and frameworks (described in detail in Chapter 4).

SYSTEMS ANALYSIS: Many systems-level configurations are possible for bioenergy systems, calling for systems analysis. For example, solvent liquefaction systems improve operations and commercialization in a continuous-feed configuration rather than batch mode. Similarly, operating combustion and liquefaction systems at small and medium scales is necessary to match the distributed nature of liquid biomass resources. And in addition to energy production, BECCS deployment has co-benefits that need to be maximized through systems analysis, including soil carbon sequestration from growing perennial grasses for feedstocks, other value-add utilization opportunities, and local economic development. Lastly, different systems-level configurations can result in trade-offs between profitability and net carbon sequestration, which must be quantified to support business model development and inform policymakers. Research should prioritize understanding which systems levers might hold the most value in terms of carbon, sustainability, and profitability, and focus on avoiding perverse outcomes (e.g., an increase in greenhouse gas emissions from nitrous oxides or poorly configured heat production).

One large facility, ADM in Decatur, Illinois, is integrated with CCS technology, and the first two autothermal fast pyrolysis plants capable of processing 50 tons of biomass per day are under construction. These vanguard plants will undoubtedly identify engineering challenges and design issues that afford opportunities to improve plant performance, and future R&D efforts can target these challenges. Substantial investment in research and engineering is also needed for product handling, storage, and marketing.

Mid-Term (3-10 years) R&D Priorities

DEVELOPMENT OF MODULAR CARBON CAPTURE RETROFIT CAPABILITY WITH BIOMASS: Given that some power plants will be converted to integrate CCS/CCU systems and run on biomass feedstocks, a range of engineering challenges are anticipated for retrofitting, co-conversion, and feedstock handling and preparation. For example, torrefaction of biomass to facilitate co-firing with coal in power plants is still in development. Carbon capture will also need to be integrated with co-firing or retrofit plants, requiring that carbon capture processes are matched with the variable scale of bioenergy and benefit from cost-effective scaling. Biomass-derived flue gas can pose challenges for conventional chemical absorption carbon capture systems and requires a distinct research agenda complementary to carbon capture from coal plants. Modular capture systems of this type would also have wider industry and carbon-to-value application (see Chapter 3).

MONITORING OF SUSTAINABILITY IMPACTS (LIFECYCLE ANALYSIS, ECOSYSTEM IMPACTS, ECONOMICS): Assessing the carbon removal impacts and other sustainability measures of terrestrial biomass systems will require new frameworks for lifecycle analysis that are flexible between different scales, continually updated based on new data, and actionable for informing best practices. Sensing technologies, such as remote and in-field sensors, must be combined with modeling tools to develop predictive science for sustainable BECCS deployment at different scales. Data collection and networks that enable sharing and evaluation are needed to bolster both the science of BECCS sustainability and the economics.

Regarding biogenic emissions, the sampling and verification priorities discussed in Chapter 4 are equally important here. Ecosystem process models also play a fundamental role in synthesizing limited empirical observations across the spatial heterogeneity present in real-world landscapes, and data-model integration is key. Such biophysical modeling forms the base of both lifecycle analysis, to understand the net climate benefits of carbon-negative bioenergy systems, and techno-economic assessments of their practical economic viability.

ADVANCED THERMOCHEMICAL AND BIOCHEMICAL PROCESS DEVELOPMENT: New process developments are needed that either have low capital costs, are able to create pure CO_2 streams as byproduct, or are amenable to modular deployment.

- Low-capital cost biomass conversion is critically needed, as capital costs are the primary barrier to developing low-cost cellulosic biofuels at scale (Lynd et al. 2017). One way to reduce capital costs is to develop processes that do not require enzymes to break down cellulose (Lynd et al. 2017). These processes overcome biomass recalcitrance via mechanical rather than chemical means. Many biological conversion processes, such as fermentation, also produce pure streams of carbon dioxide, eliminating the need for cost solvents or sorbents for separation (Balch et al 2017; Sanchez et al 2018). Conversion facilities that utilize biological processes may therefore be more easily integrated with CCS technology at lower cost if biological conversion can be processed at scale.

- Gas fermentation—using CO_2, syngas, hydrogen, or a mixture—is a process that can build on our operational experience with anaerobic sugar fermentation. New genetic engineering and strain selection tools are needed to broaden the range of products that can be delivered using this process. There are many startups in this space, including LanzaTech, Industrial Microbes, Kiverdi, Oakbio, and NovoNutrients.

- As the transportation sector electrifies, powered increasingly by renewable energy, there is a large emphasis on researching renewable alternatives to jet fuels, including efforts at U.S. Department of Energy and Department of Defense. There are opportunities to develop bioenergy-derived fuels. More traditional thermochemical conversions, such as Fischer-Tropsch, are also downscalable for bioenergy. Several facilities in the United States are developing capabilities to convert CO_2 or biomass into syngas and then hydrocarbons, including diesel and jet fuels.

- Pure streams of CO_2 for CCU and CCS can be created through novel thermochemical cycles, such as calcium or carbonate looping. These technologies hold significant promise for low-cost BECCS but are relatively immature. Research should include improved modeling, scale-up, biomass integration, and feedstock optimization.

DEVELOPMENT OF CO_2 CAPTURE AND SEQUESTRATION FROM MODULAR DISTRIBUTED SYSTEMS: The new carbon economy will require large numbers of smaller, distributed biomass systems to capture, use, or sequester CO_2 from small and medium-sized facilities, especially to move from carbon-neutral systems toward carbon-negative ones. For example, modular, scaled-down pre-combustion capture systems could be integrated with small and medium-sized gasification plants. Improved membrane systems, including new physical configurations (e.g., fluidized-bed micromembrane capsules) and materials (e.g., membranes made from microbes), could serve distributed systems better based on performance and unit capital costs. Mid-sized gasification and storage/utilization facilities should be networked with opportunities for utilization or storage of CO_2 from biomass conversion, such as autopyrolysis, gasification, and solvent liquefaction networks. Specific R&D goals should include low-capital cost systems, ease in manufacturing, and reduction of lifecycle carbon footprint, ideally toward net carbon removal.

Long-Term (10-30 years) R&D Topics

DEVELOPMENT OF NOVEL WAYS OF STORING BIOMASS CARBON: Biomass can be converted to biochar products (more detail below), and there are several ways to remove and utilize carbon in biomass:

- Biomass can be sunk to the anoxic zone of the deep ocean or buried terrestrially, where decay is slow and limited.
- Bioenergy crops can be used as long-lived products, including in bioproducts such as plastics or building materials such as hemp-based "concrete."
- Biomass can be used for other solid, long-lived products such as engineered wood.
- A shift toward deep-rooting bioenergy crops and low-impact soil management could potentially increase long-term sequestration of carbon, particularly for bioenergy crops with deep root systems (>1 meter).

Evaluation of bioenergy's large-scale sustainability impacts: The wide-scale deployment of carbon-negative bioenergy systems will bring with it the need to carefully monitor and verify their performance in order to make adjustments to system design as necessary, such as using complementary land use regulations that minimize unanticipated leakage (Rajagopal 2016). For site-level impacts and biogenic emissions in areas from which feedstocks are sourced, this is achievable through the improved monitoring and model-data integration techniques discussed above and in Chapter 4. Indirect impacts and changes in land use patterns resulting from biomass production are not directly measurable since the counterfactual case is not observable (Babcock 2009), which has led to considerable controversy in the assessment community (Kim and Dale 2011; O'Hare et al. 2011). However, as bioenergy systems are constructed and bioenergy policies enacted unevenly over time and space, we will be able to use these natural experiments to see how land use patterns change in response (Swinton et al. 2011; Wright et al. 2017; Field et al. 2018)—allowing us to validate economic models and general thinking around how growing local markets for sustainably sourced biomass leads to land use and land management changes.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

Carbon removal solutions such as BECCS play an important role in projected climate change mitigation (IPCC AR5; Fuss et al. 2014), but sufficient deployment of BECCS and other solutions that incorporate the use of bioenergy feedstocks will likely affect food security, clean energy development, biodiversity, water resources, and other metrics of value to society (Gough and Vaughan 2015; Fuss et al. 2014; Smith et al 2016). Growing bioenergy crops can be seen as another form of extractive industry—in this case, it's extracting carbon from soils. There are also perceived safety risks associated with geologic carbon storage that create barriers to CCS deployment, including with bioenergy, such as the social license to operate. The social science and policy research agenda for BECCS is critical to incorporate into all future work.

Because the deployment of BECCS requires ample and continuous biomass supply and the land to grow biomass, it is also contingent upon how societies resolve the conflict between energy needs and food security. Addressing these societal concerns will require a targeted behavioral science research agenda. There is also a need for a strong socio-economic research agenda. The lack of a regulatory framework that creates economic incentives for the production of low-carbon and, in particular, carbon-negative energy currently limits investment in these systems, which otherwise must compete directly against petroleum. Solvent liquefaction also competes directly with anaerobic digesters producing methane. There are some biomass gasification plants in the United States today, but these are small- to medium-scale and use waste biomass, such as urban yard waste, forestry residues, biomass harvested to suppress wildfires, and "fluff," the cellulose-rich fraction separated from municipal solid waste. Today, economically viable biomass gasification systems commonly receive a tipping fee or tax subsidies for processing biomass waste. In the future, these facilities need to be profitable, and for them to scale to be carbon negative, they need to be profitable with CCS. Governance issues are also relevant, and as the valuation of carbon storage becomes more important, it is essential to lay out clear guidance about how credit for carbon storage is allocated.

BIOCHAR

OVERVIEW AND KNOWLEDGE GAPS

BIOCHAR

Biochar is the solid, carbon-rich co-product of plant biomass pyrolysis and gasification. These processes convert easily mineralizable plant biomass into relatively slow mineralizing biochar. This constitutes a systems approach to carbon removal from the atmosphere that includes in many cases both engineered conversion and soil management. The carbon removed from the atmosphere via photosynthesis is returned to the atmosphere much more slowly if biomass is converted to biochar (Lehmann et al. 2006; Lehmann 2007). When applied as a soil amendment, biochar can stimulate microbial benefits (Lehmann et al. 2011), increase the soil's water-holding capacity (Masiello et al. 2015), improve nutrient availability (Liang et al. 2006; Laird et al. 2010), decrease susceptibility to plant disease (Elad et al. 2010), and remediate contaminated soils (Beesley et al. 2011; Hale et al. 2011). By enhancing soil quality, biochar application can increase crop yields (Spokas et al. 2012; Jeffery et al. 2017) and carbon return to soil, thereby further increasing soil carbon storage (Whitman et al. 2011). It also initiates a positive feedback that further increases carbon sequestration by increasing the amount of biomass that can be sustainably harvested.

ONE ASPECT OF THIS POSITIVE FEEDBACK IS A BENEFICIAL INDIRECT LAND USE EFFECT: When crop productivity increases, less land is needed to produce food, hence some marginal lands can be converted from food production back to native vegetation, thereby sequestering carbon in standing biomass and new soil organic matter. If biochar remains in soils for hundreds to thousands of years, it can provide a powerful climate change mitigation tool that simultaneously increases soil carbon storage and crop yields, particularly on low-quality and degraded soils. Recent estimates of biochar's climate change mitigation potential range from 1.1 to 3.3 petagrams CO_2-eq per year by 2030 (Woolf et al. 2010; Paustian et al. 2016; Griscom et al. 2017).

More than half of the studies on biochar as a soil amendment to date have been conducted under greenhouse conditions (Jeffery et al. 2017), with research still needed on its efficacy across soil types and over time. Similarly, more field and long-term data are needed for persistence of biochar carbon in soil (Wang et al. 2016). To maximize crop yield responses and the overall impact of biochar applications on soil carbon sequestration, a much better understanding is needed of the complex interactions among biochar, soil, crop, climate, management factors and non-CO_2 greenhouse emissions. The New Carbon Economy Consortium is well positioned to target the bioenergy equation holistically, including looking at biochar feedstock and the entire supply chain (e.g., biofuel production from woody and herbaceous biomass harvested sustainably).

TECHNICAL R&D PRIORITIES

Near-Term (1-3 years) R&D Priorities

PORTFOLIO OF BIOCHAR AND OTHER SOIL AMENDMENT FIELD TRIALS: Biochar carbon comes in diverse forms as a result of different pyrolysis or gasification techniques and biomass feedstocks (Enders et al. 2012; Schimmelpfennig and Glaser 2012; Tripathi et al. 2016). Heterogeneity of biochar quality and type can add further variation when added as a soil amendment across different geographies, climates, and soil types. To broadly deploy biochar and other long-lived bioenergy co-products as soil amendments, we need to conduct field trials that span climates, soil types, and agricultural and forestry practices where biochar could be used, while tracking soil carbon storage, broader biogeochemical and hydrologic cycles, and agricultural yields. The New Carbon Economy Consortium spans sites across the United States and can serve as the initial network of field trials for biochar and other soil amendments.

PLANT GROWTH RESPONSES: Additions of biochar may increase crop yield by stimulating microbes (Lehmann et al. 2011), increasing the soil's water-holding capacity (Masiello et al. 2015), improving nutrient availability (Liang et al. 2006; Laird et al. 2010), decreasing susceptibility to plant disease (Elad et al. 2010), and remediating contaminated soils (Beesley et al. 2011; Hale et al. 2011). As with any soil amendment, different biochars applied to different soils and crops generate different yield responses (Jeffrey et al. 2017). Near-term research should test the combination of biochar type, soil type, climate, and crop, on yields and soil carbon sequestration potentials.

LIFECYCLE ANALYSES (LCAS): An ability to accurately predict the net greenhouse gas impact of biochar applications is critically needed in the new carbon economy, both for assigning carbon credits to agricultural practices that include biochar applications and evaluating policy options that incentivize its use. Biochar production relies on similar biomass feedstocks as BECCS and other bioenergy technologies, thus has the same sustainability issues and assessment challenges. Biochar lifecycle analyses must also account for the persistence and associated carbon storage value of the biochar itself, as well as any effects of biochar on agricultural system productivity and soil trace gas emissions of N_2O or CH_4 (Laird 2008; Cayuela et al. 2014). Lifecycle analyses of biochar should continue to evolve as field trials yield relevant results on the impacts of biochar production and application across a range of sites.

Mid-Term (3-10 years) R&D Priorities

BIOCHAR PERSISTENCE: For biochar to provide a long-term climate change mitigation tool, a significant proportion should remain in soils for hundreds to thousands of years. However, most mineralization and crop yield studies on biochar as a deliberate soil amendment to date have been short term—less than three years—and took place in the greenhouse (Wang et al. 2016). Longer-term studies that track soil carbon transformations and stabilization are needed to optimize biochar application for systems where it can achieve the desired effect of increasing long-term soil carbon storage.

MARKET ANALYSIS FOR BIOCHAR AND OTHER LONG-LIVED PRODUCTS: The cost of biochar application is strongly influenced by production method and application rate (Williams and Arnott 2010). Field trials should include market analyses that optimize application rates and methodologies and identify regions of the United States where biochar and other long-lived bioenergy co-products can be in high demand, overcoming cost barriers and, where possible, providing additional agricultural revenue.

"WORKING FOREST" BUSINESS MODELS: Harvesting biomass for bioenergy can bring benefits such as fire hazard reduction and support for sustainable rural livelihoods. There are also opportunities to expand laminated timber and mass timber construction (Robertson et al. 2012; Crawford and Cadorel 2017). New business models can connect the production of co-benefits with carbon removal and storage and find ways to monetize both, with positive outcomes for rural livelihoods. Strategies that bring additional revenues may include harnessing existing forestry-based markets and developing markets for new long-lived wood products and soil amendments.

DISTRIBUTED SYSTEMS: Biomass resources are widely geographically distributed, and variable feedstocks produce variable biochars, with distinct characteristics. To optimize these geographically distinct systems, hybrid systems that produce biochar can be tested on agricultural and forest feedstocks that vary in the quality of energy produced and the biochar co-products they can create. These systems would likely need to be modular to address the distributed nature of the resources and the size of the biochar production opportunity in any one location.

MODELING: Capacity building is needed to predict the net impact of biochar applications on soil carbon sequestration and net greenhouse gas emissions, which requires mechanistic models that account for complex interactions among biochar, soil, climate, crop, and management systems. Process-based models are essential to understand these interactions, which can influence crop yield and environmental responses to biochar applications, and they must be calibrated and validated using data from long-term field trials across diverse soils, climates, and management systems. In addition, the stability of biochar in soils is most often roughly inferred from its chemical composition, but the newest generation of ecosystem process models are beginning to incorporate stabilization mechanisms for soil carbon, including natural black carbon and anthropogenic biochar, more explicitly (Schmidt et al. 2011; Cotrufo et al. 2013), and they should be integrated with other modeling approaches, including LCA.

Long-Term (10-30 years) R&D Topics

GLOBAL POTENTIAL FOR CARBON SEQUESTRATION: To fully realize the potential for biochar to increase carbon sequestration in soils, we need a better understanding of the complex interactions among biochar, soil, crop, climate, management factors, and non-CO_2 greenhouse emissions—a knowledge gap that the New Carbon Economy Consortium is well positioned to address. Near- and mid-term foundational research endeavors described above will form the basis for the longer-term research agenda.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

The use of biochar as a soil amendment to agricultural soils can be an important win-win for carbon management and agricultural productivity; however, building a biochar industry large enough to remove a significant amount of carbon from the atmosphere requires substantial interdisciplinary research in agronomy, engineering, macroeconomics (markets and policies), and techno-economic analyses (supply chain and site-specific plant design). This presents an opportunity for cross-cutting social science research.

AQUATIC AND TERRESTRIAL ALGAE AND BIOLOGICAL COMMUNITIES

OVERVIEW AND KNOWLEDGE GAPS

ALGAE

Production of algae—both photosynthetic microalgae, including cyanobacteria, and macroalgae, such as kelp—captures atmospheric CO_2 and produces biomass, creating many potential routes to carbon removal and utilization. Algae's exceptional growth rate and productivity relative to terrestrial crops holds the potential for significant intensification of biomass production, while algae's ability to grow without the use of productive soil or potable water does not conflict with the agricultural sector.

Microalgae production systems can be sited close to bioenergy or other biomanufacturing facilities and used to capture and utilize flue CO_2 (Pate et al. 2011; Venteris et al. 2014). Several pilot and demonstration-scale algae CCUS projects are now in operation at fossil-fueled generating stations, cement plants, and other industrial facilities, including ethanol plants, breweries, and other sources of biogenic carbon emissions. The 2016 U.S. Department of Energy's "2016 Billion-Ton Report" (Langholtz et al. 2016) estimates there is suitable land for cost-effective co-location of algae CCUS at more than 100 U.S. ethanol plants, with the potential to capture nearly 30 million tons per year from these facilities.

The biomass produced from algae cultivation can be converted into various low-carbon, carbon-neutral or potentially carbon-negative products. Microalgae bioreactors can also utilize nutrients in industrial, agricultural, and municipal sewage effluents, simultaneously capturing CO_2 and cleaning waste waters (Craggs et al. 2011). In arid regions where fresh water resources are limited, microalgae can be produced using salt water to avoid competition with agriculture and urban uses.

The key technical challenges for developing and scaling robust microalgae systems pertain to land availability, especially near CO_2 sources, algal crop loss due to pond crashes, and certain aspects of downstream handling and processing. Sunny locations are optimal for algae growth, but water availability becomes a challenge. Predation and competition from wild algae strains have thus far limited the use of highly efficient and advanced microalgae strains in open bioreactors to a handful of species, while capital costs associated with industrial-scale production using advanced microalgae strains in closed reactors has been limited to higher-value product markets such as nutritional supplements. Of particular importance is the need for a functional understanding of the ecological interactions between algae and surrounding microorganisms in open systems that can affect productivity.

As algae production becomes optimized and efficient, price parity with other bio-energy products, such as switchgrass and softwood trees, becomes more realistic. Beyond their potential utility in providing low-carbon bioenergy products, algae can be used to produce valuable sustainable products such as feed, food, and complex chemicals, which could spare land and provide carbon mitigation opportunities. Many species of algae have highly evolved biochemical synthesis pathways and are also amenable to biological engineering, allowing them to serve as a powerful platform for generating valuable lipids, proteins, nutraceuticals, and other complex chemicals with substantially reduced carbon footprints.

The production of algae-derived sustainable and renewable products occurs through the direct utilization of CO_2 without requiring the use of fertile land. While some analyses have concluded that products derived from nonbioenergy algae could offer greater overall carbon benefits by sparing land and avoiding the associated greenhouse gas implications, algae have higher productivity per area than terrestrial crops, and the land use required to cultivate a given amount of algae biomass—regardless of its downstream use—would be less than the same mass in other terrestrial crops. That land saved could be used for other uses, such as perennial forests that maximize carbon retention or food production for a growing population.

In addition to algae, other microbial platforms also hold signficant potential for CCUS. Several technologies are under development for microbial CCUS that can be co-located with bioenergy, biomanufacturing, or other biogenic carbon sources for net carbon-negative systems.

BIOLOGICAL COMMUNITIES

Biological communities, in particular microbial communities, are the primary drivers of organic matter decomposition and stabilization (Kallenbach et al. 2016) and a key indicator of soil carbon storage. With the advent of low-cost sequencing methods, microbial communities can be assessed, and though we are in the early days of manipulating microbiomes (Wallenstein et al. 2017), future work can focus on optimizing for desired functions using a variety of emerging techniques. For example, recent advancements in microbiome sciences and the advent of cheap sequencing have helped shed light on the roles of specific microbe groups in soil processes and plant growth. These insights can inform the development of next-generation methods that target microbial functions in hybrid biological and engineered systems. For example, microbes produce extracellular enzymes that degrade complex carbon molecules (Allison et al. 2011), and a research agenda should target carbon enzymes—either downregulation or upregulation, depending on context. Certain microbial innocula can help facilitate certain processes to break down biomass into desired co-products and fuels (e.g. LanzaTech) or further promote stabilization of carbon in biochar and other long-lived biomass products (Lehmann et al. 2011).

TECHNICAL R&D PRIORITIES

Near-Term (1-3 years) R&D Priorities

MICROBIAL ENGINEERING

- *Electroactive microbes:* As transportation becomes increasingly electrified and battery storage capacity vastly expands to capitalize on intermittent renewable energy resources, addressing oxide formation on battery electrodes becomes increasingly important. Electroactive microbes such as S. oneidensis can remove electrode oxide layers, but their viability and function are compromised by battery electrolyte. Advanced genetic tools should be applied to isolate microbes that can thrive in harsh environments, such as those inside batteries, and engineer microbial communities to function inside batteries and restore energy storage capacity.

- *Microbially derived biofuels:* Microorganisms that produce oil, such as the yeast Yarrowia lipolytica, offer promising pathways to sustainably produce advanced biofuels, including gasoline, diesel, and jet fuel (Abghari and Chen 2014). Advanced genetic tools (e.g., CRISPR/Cas9) and automated genome evolution can be utilized to select for favorable traits that increase efficiency of fuel molecule production and allow for these microbially derived biofuels to scale.

- *Microbiome engineering:* Without genetic modification, microbial communities can be fostered by adding specific microbes of interest or functional groups of microbes with desires attributes (e.g., high C:N ratios or symbiotic microbes that help create products of interest). Microbial communities need to be optimized to target specific feedstocks or conditions.

ALGAL MANAGEMENT: Algae handling and processing can be greatly improved and yield carbon benefits, including reduced overall emissions and more efficient water use.

- *Dewatering:* The development of a cost-effective means of dewatering microalgae biomass is needed. Microalgae production systems should prioritize recycling water, and vast improvements in water efficiency can both improve biomass yields and reduce the overall footprint of algal operations.
- *CO2 management:* Safe and efficient CO_2 capture, transport, and distribution systems developed for other CO_2 management purposes (Chapter 3 - engineered solutions) can also be applied to microalgae production facilities. Major opportunities for research and development are in improving CO_2 delivery to algae biomass, integrating algae systems with existing emission point sources, and developing algae strains that can utilize non-pure CO_2 flue streams.
- *Siting:* Microalgae systems can be sited near industrial CO_2 sources, reduce the carbon footprint of those industries, and provide immediate opportunities for co-products development. Therefore, microalgae system should be scalable to match the size of the CO_2 sources. This creates a clear opportunity for modular systems that can flexibly stack to take advantage of economies of scale and optimize operations around algal strains with the widest range of climate tolerance or resource utilization tolerance.

ALGAE CO-PRODUCTS DEVELOPMENT, INCLUDING GENOMICS AND PROTEOMICS: Algae can be used to produce liquid fuels and a suite of other co-products, including soil amendments (discussed in Chapter 4), proteins, lipids, and fatty acids for food supplements or animal feed, pigments, and novel antibiotics. Basic and applied research can help incorporate the full diversity of algae and identify algal strains that can make multiple products and deploy across a wider range of sites. The production of algae co-products can be improved by zeroing in on specific algal species and optimal growing conditions, improving algae handling and processing, developing cost-effective means of dewatering microalgae biomass, and developing modular and scalable conversion technologies. There are a range of additional benefits associated with more efficient algal processing and conversion systems, including the ability to recycle water and reducing the need for land cultivation and the associated greenhouse gas emissions.

Integration of algae and microbes: Microbiome engineering—adding specific microbes of interest without genetic modification—can help harness the power of symbiotic microbes to make products of interest from algal waste. Certain components of algal biomass can be utilized specifically for carbon sequestration instead of burning and releasing it back into the atmosphere later, but this requires an explicit and potentially monetizable benefit of carbon sequestration relative to combustion.

"SWEET SPOT" ANALYSIS THAT TARGETS SUSTAINABLE NUTRIENT MANAGEMENT: Algae systems must be located in regions with CO_2 and water sources and the means to process algae and produce fuels and other co-products, requiring a "sweet spot" systems analysis.

Mid-Term (3-10 years) R&D Priorities

INDUSTRIAL-SIZE MICROALGAE SYSTEMS: As renewable electricity becomes cheaper and readily available, artificially illuminated photobioreactors offer the potential to further industrialize microalgae cultivation and increase productivity. This is especially relevant if algae systems are integrated into industrial-scale carbon management, where large CO_2 streams need to be utilized on-site or stored. Systems-level work that optimizes CO_2 delivery and maximizes algae growth is needed to make algae cultivation a viable industrial-scale CCU option.

LARGE-SCALE OUTDOOR SYSTEMS DEVELOPMENT: The few algae systems in operation today are relatively small. Large outdoor systems must be developed and tested to scale algae utilization to match the new carbon economy's scale of need for alternative liquid fuels to displace fossil fuels and for CO_2 utilization to match the scale of carbon emissions. In the mid-term, the New Carbon Economy Consortium can build demonstration-scale microalgae-CCU plants coupled with industrial CO_2 sources that also support other environmental services, such as wastewater remediation. In the longer term, these systems can grow to commercial scale, especially as systems integration and optimization issues are addressed.

SOCIAL, LEGAL, ECONOMIC, AND POLITICAL RESEARCH GAPS

Harnessing aquatic and terrestrial algae to utilize CO_2 and produce a range of products necessarily combines both biological and engineered approaches and their associated suite of socioeconomic, policy, and legal concerns. Where terrestrial and aquatic disciplines come together, federal agencies that fund basic and applied research (e.g., U.S. Department of Energy, Department of Agriculture, National Oceanic and Atmospheric Administration, Department of Defense) will have to co-fund research programs and agree on success metrics where their missions align. Businesses built around algae fuels and other co-products will need to educate consumers about these products, resolve supply chain uncertainties, and develop markets not only for the products, but also for their carbon benefits. Enabling algae products to compete in today's markets will require initial and transitional policy supports until their carbon benefits are more easily accounted for and monetizable.

CROSS-CUTTING OPPORTUNITIES

Hybrid biological and engineered solutions necessarily cross disciplinary boundaries and present a unique opportunity to optimize several climate-beneficial areas, including increasing soil carbon, producing biofuels, improving soil productivity, thereby reducing cultivated acreage, and bringing the benefits of the new carbon economy to all geographies and people across socioeconomic groups. Until now, federal funding agencies have compartmentalized research on bioenergy production and soil agroecosystem management, often resulting in disjointed and incompatible visions from the engineers designing bioenergy production facilities and the soil scientists and agronomists designing sustainable biomass production systems.

Lifecycle analyses present a critical cross-cutting research area that is necessary for biological and engineered solutions. As noted above, lifecycle analyses are essential to determine the net impact of hybrid systems on greenhouse gas emissions, including both direct effects on carbon emissions due to harvest, storage, and transport of biomass, relative to the displacement of fossil fuel, and indirect effects on soil health, food production and security, and land use (Roberts et al. 2009).

RESOURCES REQUIRED

HUMAN CAPITAL

For hybrid biological and engineered carbon removal solutions to reach their full potential, research and development require collaboration across often siloed scientific disciplines. This is true within industry, academia, government, and other sectors. In academic institutions, engineering departments will need to work with agriculture and ecology departments. In industry, the sustainable deployment of BECCS requires the development of both technology and sustainable biomass supply, a research agenda that spans several federal agencies and requires collaborative funding. In the United States, there is substantial opportunity for collaborative R&D through interagency coordination at the federal level, including through the White House Office of Science and Technology Policy and the U.S. Global Change Research Program, or through agency reorganization. Potential interagency efforts include technology roadmapping, information sharing, stakeholder engagement, and international engagement (Sanchez et al. 2018).

Multiple engineering types are critically needed for the design, development, testing, and scaling of bioenergy production facilities for all three major approaches to bioenergy discussed here: pyrolysis, gasification, and solvent liquefaction. Agronomy, soil science, and system modeling are needed for biochar laboratory and field trials, and to build, calibrate, and validate the mechanistic biochar model(s). Agronomy, forestry, soil science ecology, and agricultural engineering are needed to assess the viability and sustainability of biomass production, storage, and transport systems. Engineers, economists, and scientists trained in lifecycle analysis and techno-economic modeling are needed to evaluate the economic viability of developing and deploying various low-carbon and carbon-negative bioenergy systems and to assess their environmental impact in different regions and scales. Business, finance, and policy studies are needed to develop and evaluate business models and transition carbon-negative bioenergy systems through the pilot, demonstration, and industrial scales.

DATA INFRASTRUCTURE

Hybrid biological and engineered approaches will require the integration of data from diverse sources and new data-sharing platforms. For example, coupling soil carbon data with aboveground energy crop production is a key synergy for sustainable energy production. Robust databases integrated with systems modeling will be required to make progress in testing different approaches for producing and deploying biochar for microalgae-CCU, as well as for coupled economic and policy analyses. Existing soil, climate, crop, land use, and techno-economic databases can be leveraged to assess sustainable biomass supplies, biochar impacts on agronomic and environmental endpoints, and policy outcomes. For microalgae-CCU, a network of research centers is needed to focus on process modeling required to scale and interface microalgae-CCU systems with new and existing bioenergy production facilities that generate CO_2.

MODELING

Current accounting conventions treat carbon sequestration as the inverse of an emissions pulse of CO_2 to the atmosphere, which accounts for the eventual fate of that CO_2, including its uptake by the terrestrial biosphere and oceans over different timescales. This is a reasonable assumption today, as the total rate of greenhouse gas emissions is still increasing, and "negative emissions" can be thought of as a marginal reduction in those net positive emissions. However, if and when atmospheric CO_2 levels are stabilized and start to fall, these accounting conventions become obsolete in the face of carbon cycle feedbacks and oceanic carbon outgassing (Rickels et al. 2018). Thus, it will become important to develop new scenario-based performance metrics capable of quantifying the unique role of carbon-negative bioenergy and other negative emissions technologies within the wider decarbonization portfolio and ensure that those metrics are well represented in the IPCC models. In addition, we need a new modeling framework that integrates macroeconomic, techno-economic, lifecycle analysis, process engineering, agronomic, and environmental models to support systems-level assessments of environmental impact and policy and business model development.

As IPCC models focus more on carbon removal, ecosystem process models vary in their formulation and ability to extrapolate past current conditions and predict ecosystem properties in a changing climate (De Kauwe et al. 2013). It will become important for bioenergy assessment studies to replace individual ecosystem models with model ensembles to capture these fundamental structural differences and the resulting limitations of model-based predictions. Model intercomparison projects, such as the Agricultural Model Intercomparison Project (http://www.agmip.org/) and the Carbon Dioxide Removal Model Intercomparison Project (https://www.kiel-earth-institute.de/CDR_Model_Intercomparison_Project.html), will likely play a key role in coordinating the logistically difficult and computationally intensive process of coordinating models implemented in different programming languages and with vastly different spatial resolution, data requirements, and I/O procedures. This process has been widely and effectively used in the atmospheric science world, with the Climate Model Intercomparison Project providing statistically rigorous ensemble run results representative of the range of different climate model formulations. Model testbeds designed and curated to compare models of terrestrial biological and hybrid carbon dioxide removal approaches would catalyze development, increase scientific rigor, and enhance policy relevance.

BIOCHAR MODELS

Mechanistic biochar models (Foereid et al. 2011; Whitman et al. 2011; Woolf and Lehmann 2012) that predict agronomic and environmental (e.g., greenhouse gas and water quality) outcomes need to be fully developed, calibrated, and validated across a wide range of soils, climates, crops, and management systems. Biochar models need to move toward being able to operate at the soil pedon, field, regional, and global scales to support individual farmers and broader policy assessments. We must build the capacity to predict the net impact of biochar applications on soil carbon sequestration and net greenhouse gas emissions, requiring mechanistic models that account for complex biochar, soil, climate, and crop management interactions. An ability to accurately predict the net greenhouse gas impact of biochar applications is critically needed in the new carbon economy, both for assigning carbon credits to agriculture practices that include biochar applications and for evaluating policy options that incentivize its use. Scientific studies are needed to iteratively refine, calibrate, and validate process-based biochar agroecosystem models.

TESTBEDS

To understand how to scale new carbon economy solutions, testbeds are essential. Testbeds are smaller projects distributed across the United States that use the same methodologies across sites that vary in biomass feedstocks, climates, and geologies. The following should be prioritized:

1. Pilot and demonstration-scale plants that convert biomass to products are needed:
    - A. For continuous-feed solvent liquefaction;
    - B. For continuous-feed pyrolysis using multiple liquid and gaseous energy products;
    - C. To evaluate the utilization of multiple feedstocks, including problematic wastes, and the production of bioenergy co-products, including biochar;
    - D. To test microalgae-CCU systems adjacent to existing small-scale industrial CO_2 sources.
2. Funding is needed to support research that assesses the handling and upgrading of biofuel products, and to support laboratory, greenhouse, and field trial research with biochar products.
3. Testing of bioenergy production, such as from plantation pine in the U.S. Southeast, needs to be conducted in conjunction with soil biochar amendment and complete lifecycle assessment to optimize forestry, agriculture, and bioenergy simultaneously.
4. Coordinated long-term biochar research plots must be established in major agricultural zones across the United States, especially in poor soils, for the most common biochar types and using agreed-upon assessment protocols.
5. Development of a modeling testbed needs to allow comparison of different biochar models and the comparison of scenarios based on an ensemble of models.

Testbeds and field trials are critical to building robust models as they enable process models to be calibrated and ultimately validated using data from diverse soils, climates, and management systems. For example, biochar as a soil amendment has great potential, but it would benefit from long-term large-scale field trials in regions most likely to benefit from its use. Currently, the sole incentive for farmers to purchase and apply biochar to agricultural fields is the positive crop-yield response to biochar applications. Farmers will demand local field trials before they will adopt such practices at the scale necessary for significant carbon removal from the atmosphere.

RESEARCH NETWORKS

Research centers for biochar, microalgae-CCU, and economics-policy research, envisioned as the foci of research networks, will promote and coordinate long-term sustained research efforts across multiple locations. These centers will work in partnership with foundations and government funding agencies to ensure long-term sustained funding. The overlap between energy and agriculture makes private sources of funding especially important, as many of the critical questions cannot be answered in the typical three-year funding cycle of federal grants, and government programs do not cross the energy-agriculture boundary readily.

A biochar research center is needed to coordinate laboratory, greenhouse, and field studies that iteratively update, calibrate, and validate the development of process-based ecosystem models capable of simulating biochar's effect on nutrient cycling, plant productivity and biogeochemistry (e.g., the Agricultural Production Systems sIMulator model[1] or similar). A biochar research center is also needed to provide sustained funding for long-term multilocation biochar field trials targeting soils and agricultural production systems that would likely benefit from biochar applications.

NEAR-TERM OPPORTUNITIES FOR PROGRESS

The New Carbon Economy Consortium will take a wide view of the need for distributed biomass processing and associated opportunities for carbon capture, storage and utilization across distributed networks. Much prior research on bioenergy has attempted to capture economies of scale by focusing on centralized processing facilities and ignoring the reality that biomass resources are diffusely distributed and logistically challenging. The Consortium will seek the optimum scale, while balancing economies of scale in processing facilities with increasing feedstock costs that grow with facility size. A prime near-term opportunity for the New Carbon Economy Consortium to build momentum is to move to establish the three centers that focus on biochar, microalgae-CCU, and economics-policy research.

Chapter 6: Findings and Recommendations

Throughout this innovation plan, we have outlined a wide range of multidisciplinary research gaps and priorities. In this chapter, we aggregate and translate these gaps and findings from the technical chapters into concrete cross-cutting recommendations. We have also outlined the resources and infrastructure needed to activate the innovation plan's ambitious research agenda. These recommendations will guide the Consortium's core functions over the coming years.

FINDINGS AND RECOMMENDATIONS: KNOWLEDGE AND RESOURCES

FINDING 1: *There is a fundamental gap in integrated knowledge related to strategies for building the new carbon economy.* In preparing this innovation plan, it became clear that carbon management and its potential economic opportunities were poorly represented in scientific literature, policy discussions, techno-economic analyses, and public discourse as a whole. In part because of the interdisciplinary and rapidly evolving aspects of many scientific and technical components, there was even less recognition of either the potential viability of emerging R&D areas and deployment opportunities or the potential limitations of current approaches. This was true for engineered, biological, and hybrid approaches.

FINDING 2: *There are very few R&D programs supporting key elements of the new carbon economy, and their funding level is insufficient to deliver breakthroughs.* Both in the United States and worldwide, the opportunity for leading researchers and research institutions to receive funding for R&D is extremely limited. In the United States, the 2018 federal budget allocated the Department of Energy to spend no funding on direct air capture, and only $12 million for CO_2 conversion. Funding for biological carbon storage is much more difficult to estimate because it spans disciplines, such as soil science, forestry, agriculture and bioenergy, and large federal agencies and programs, including the U.S. Department of Energy, the Department of Agriculture, the Department of Interior, the Forestry Service, the National Park Service, and National Science Foundation. This was complicated further by the difficulty of siloed research programs in sponsoring interdisciplinary work (e.g., integrating bioenergy, biochar production, and soil carbon science).

RECOMMENDATION 1: *Widen the range of R&D programs serving the new carbon economy and increase their funding.* Federal funding agencies, such as the U.S. Department of Energy, Department of the Interior, Department of Defense, National Science Foundation, and National Aeronautics and Space Administration, can examine existing R&D programs and identify gaps and limitations in their support of the new carbon economy. External experts in key disciplines can be engaged through workshops and planning processes for basic research needs. There is also a need to coordinate between internal offices and across governments to highlight the most promising opportunities and avoid overlap, duplication, and waste. Based on these efforts, these agencies can consider additional funding lines within or adjacent to existing programs that would expand their scope to explore core research and development topics for the new carbon economy. Government or industry funding platforms can ideally be long-lived to support scientists and practitioners and allow promising students to complete their work and training. Lawmakers can consider adding report language that helps identify important programs and outcomes, as well as direct components of spending to those ends. Long-lived and stable funding will allow technical work to launch and complete foundational research tasks.

RECOMMENDATION 2: *Create a new carbon economy secretariat.* Philanthropy, civil society, and industry can support the creation of a new carbon economy secretariat. A secretariat is the only means by which acceleration of all recommended actions can be accomplished, as it carries the responsibility to rapidly gather and fund research teams, disseminate information from new carbon economy research and development actors, and prepare reports on the state of the new carbon economy and its components. The secretariat would help support the convening to discuss and explore issues and opportunities pertaining to the new carbon economy and host an annual symposium to share important points of progress and results.

FINDINGS AND RECOMMENDATIONS: LIMITS TO OPPORTUNITY

FINDING 3: *Every discipline pertinent to the new carbon economy includes near-term, high-impact endeavors that are not fully mapped.* Each of the primary R&D pathways discussed in Chapters 3, 4, and 5 present near-term opportunities for rapid research progress and early deployment and learning. But the relative impact of those opportunities across disciplines has not yet been comprehensively analyzed. A short-term, targeted effort to better resolve these opportunities geographically and topically would serve researchers, sponsors, and investors alike and help to ensure that resources flow to the highest-impact opportunities. In many cases, substantial progress could be made in one to three years with modest investments.

FINDING 4: *There are limited fora to discuss and address R&D needs in all new carbon economy disciplines.* There are no journals dedicated solely to carbon removal, carbon-to-value, or carbon intensification and sequestration in natural systems, and the body of knowledge for the new carbon economy is spread across academic disciplines and research labs. Although the number of publications and conferences on carbon removal and carbon-to-value is growing, more—and a more diverse set of—platforms are needed to engage professionals and thought leaders in the new carbon economy.

FINDING 5: *Many topics in the new carbon economy are inherently interdisciplinary, requiring a mixture of bench, field, and social science approaches to bring key opportunities to markets and stakeholders.* Many efforts within the carbon removal solutions described in Chapters 3, 4, and 5 require a mixture of technical disciplines (e.g., physics with engineering or biochemistry with soil science) and social science disciplines (e.g., economics, behavioral science, decision support tools). Traditionally, it has been difficult for R&D programs to fund interdisciplinary work, and differences across technical cultures limit collaboration opportunities. New and/or expanded platforms that encourage interdisciplinary work for the new carbon economy, especially those that feature both technical and social science disciplines, are needed to make rapid progress in developing economically feasible carbon removal pathways that overcome challenges limiting their adoption.

RECOMMENDATION 3: *Map opportunities.* As an early priority, Consortium institutions can select topics and teams to map national and global opportunities for research, development, and demonstration of key new carbon economy pathways and share them publicly, ideally through open access platforms and fora (and the secretariat of Recommendation 2.)

RECOMMENDATION 4: *Convene workshops*. As an early priority, Consortium institutions can convene meetings focused on the central topics holding back the emergence of the new carbon economy. These should be both disciplinary and interdisciplinary. Workshops that explore R&D and scholarship in sociology, economics, law, and political science related to the new carbon economy can be specifically included, with future fora incorporating conventional technical and social science disciplines. The proceedings and findings of these workshops should be made public.

FINDINGS AND RECOMMENDATIONS: HUMAN CAPITAL

FINDING 6: *There are few programs that train experts in the integrated disciplines of the emerging new carbon economy.* Today, there are few experts and practitioners working to achieve the new carbon economy's environmental or economic goals. Universities lack curricula and capacity to support fellowships that focus on carbon removal, and few of the existing initiatives in this area are interdisciplinary. Companies and universities offer far too few internships to give students opportunities to learn by doing. The people who will create future professional societies have not been trained. New students and potential practitioners interested in applying their talents to the new carbon economy cannot enroll in programs specifically attuned to this economy, as the key topics remain spread across a multitude of departments, schools, and disciplines. This fragmented landscape is reinforced by the lack of funding in new carbon economy endeavors and absence of widespread awareness of the necessary work and potential opportunities (Findings 1 and 2 above).

RECOMMENDATION 5: *Create curricula.* Universities can encourage deans and research faculty to create interdisciplinary clusters and courses that address new carbon economy topics. Since the new carbon economy is under development, many of these courses will include a significant conceptual, exploratory component, bringing new and fresh ideas into the new carbon economy research agenda. New programs could also incorporate on-site carbon removal projects, giving direct opportunities for hands-on learning.

RECOMMENDATION 6: *Establish training programs.* Universities, national labs, and other R&D centers can create training programs to support research and human capital development focused specifically on the new carbon economy. Potential efforts include creation of fellowship and internship programs in disciplinary and cross-disciplinary new carbon economy work, as well as travel support to new carbon economy workshops.

FINDINGS AND RECOMMENDATIONS: COLLABORATION AND SCIENTIFIC INFRASTRUCTURE

FINDING 7: *Although assets and infrastructural elements for the new carbon economy partially exist today, they are distributed and often isolated from interested researchers, research institution leaders, business leaders, and policymakers.* Testbeds, data-sharing platforms, and centers of excellence are beginning to emerge across a number of Consortium participant institutions. However, we need greater scale and connectivity of this initial infrastructure for scientific exploration and the joint creation and dissemination of knowledge around the new carbon economy. These platforms for collaborative research and knowledge sharing are insufficiently resourced to provide these services, and they need to improve and expand their data sharing and aggregation capabilities and standardization of process and results.

FINDING 8: *A lack of consistent frameworks and standards for discussing and measuring the techno-economic and carbon-sequestering solutions limits their uptake and deployment.* Standards and protocols that could serve to enhance or optimize environmental or economic goals in the new carbon economy are limited to nonexistent today. Measurement and assessment standards and protocols are required to support the development of lifecycle analyses, policy elements related to the new carbon economy, optimization of economic or energetic benefits, and rational investment strategies. Missing components for biological, engineered, and hybrid approaches include standardized units, accepted protocols, baseline data, accepted simulation and modeling platforms, and validated tools. Even simple outcomes, such as carbon-content labeling of goods, are not possible today. A concerted effort is required to develop standards and protocols for industrial, governmental, or regulatory adoption.

RECOMMENDATION 8: *Develop and deploy testbeds.* The mission and work of the New Carbon Economy Consortium should include developing platforms to test carbon uptake, utilization, and storage, and templates for measurement and verification, lifecycle analyses, mechanistic modeling, and techno-economic comparison. Also needed are networked and expanded field-scale testbed facilities to test performance and efficacy of solutions across geographies and soil types (e.g., agricultural testbeds), with results shared nationally and internationally. Existing testbeds within the New Carbon Economy Consortium should be encouraged to open their operations to a national and international set of partners and share results in open access platforms, excluding proprietary results. In addition, new testbeds, including those outlined in Chapters 3, 4, and 5 of this innovation plan, should be initiated to cover important new and emerging topics with federal, state, philanthropic, and/or industrial program support. This testbed network should also be used to test standardized, low-cost data collection and modeling tools, data repositories, and performance and accounting standards.

RECOMMENDATION 9: *Support data aggregation, sharing, and modeling.* Universities and national labs that are part of the New Carbon Economy Consortium should create and support new platforms to compile, aggregate, analyze, and share data. These include biological, genetic, thermodynamic, kinetic, process engineering, simulation, and techno-economic data, as well as sociological and economic modeling data. For large data volumes, platforms of common interest should form and federate. These data should be used to update and develop modeling platforms to support the new carbon economy, including lifecycle and techno-economic modeling.

RECOMMENDATION 10: *Create and invest in centers of excellence. As appropriate, sponsors and host institutions should create and support centers of excellence for new carbon economy studies.* These could proceed under a number of funding models and operational models (e.g., the U.S. Department of Energy's Energy Frontier Research Centers or Energy Innovation Hubs, or the National Science Foundation's Integrative Graduate Education and Research Traineeship structures). These centers would help support and maintain research infrastructure critical for the scaling up and success of the new carbon economy, and serve as training platforms and human capital draws for future development.

FIGURE 12. *Findings and Recommendations*

Significant work is required to realize a new carbon economy. Based on the technical gap identification in Chapters 3-5, we recommend a series of activities to be pursued by the Consortium and other institutions over the coming years.

	FINDINGS	RECOMMENDATIONS
KNOWLEDGE AND RESOURCE GAP	• There is a fundamental gap in integrated knowledge related to strategies for building the new carbon economy • There are very few R&D programs supporting key elements of the new carbon economy, and their funding level is insufficient to deliver breakthroughs	• Widen the range of R&D programs serving the new carbon economy and increase their funding • Create a New Carbon Economy Secretariat to rapidly gather and fund research teams, disseminate information, and prepare reports on the state of the new carbon economy and its components
LIMITS TO OPPORTUNITY	• Every discipline pertinent to the new carbon economy includes near-term, high-impact endeavors that are not fully mapped • There are limited fora to discuss and address R&D needs in all new carbon economy disciplines • Many topics in the new carbon economy are inherently interdisciplinary and, in many cases, require a mixture of "bench," field, and social science approaches to bring key opportunities to markets and stakeholders	• Select topics and teams to map national and global opportunities for research, development, and demonstration of key new carbon economy pathways • Convene disciplinary and interdisciplinary meetings and fora around the central topics holding back the emergence of the new carbon economy
HUMAN CAPITAL	• There are few programs that train experts in the integrated disciplines of the emerging new carbon economy	• Create interdisciplinary clusters and courses that address new carbon economy topics • Establish training programs to support research and human capital development focused specifically on the new carbon economy
COLLABORATION AND SCIENTIFIC INFRASTRUCTURE	• Although assets and infrastructural elements for the new carbon economy partially exist today, they are distributed and often isolated from interested researchers, leaders of research institutions, business leaders, and policymakers • The lack of consistent frameworks and standards for discussing and measuring the techno-economic and carbon-sequestering potential of solutions limits their uptake and deployment	• Develop platforms and test beds to analyze carbon uptake, utilization, and storage, and create templates for measurement and verification, lifecycle analyses, and techno-economic comparison • Create and support new platforms to compile, aggregate, analyze, and share data • Sponsors and host institutions should create and support centers of excellence for new carbon economy studies

Summary

THE NEW CARBON ECONOMY'S ECONOMIC AND ENVIRONMENTAL OPPORTUNITIES ARE LARGE BUT REQUIRE ADDITIONAL ACTIONS TO BE FULLY REALIZED.

The Consortium's early work suggests both large opportunity and growing interest in the new carbon economy, although additional research is required to understand its full economic and environmental potential. Substantial gaps in knowledge, skills, tools, and institutional infrastructure must be addressed. Dramatic increases in funding, academic focus, and institutional investments are needed to rapidly deliver the full promise of the new carbon economy. This will require developing robust, scholarly, and long-lived R&D programs, building research infrastructure, and growing human capital.

Tangible, near-term successes and a concerted, strategic, and long-lived R&D effort are necessary to catalyze the scaling up of diverse carbon removal and utilization approaches that are critical in a prosperous economy that extracts and stores more carbon from the atmosphere than it emits. Near-term successes will enable policymakers around the world to develop incentives and supports and create the markets and industrial hubs necessary in the new carbon economy. Fellowships and grants can support research that sparks entrepreneurs into founding new companies, some of which will grow into the corporate giants of the 21st century. Students and postdocs involved in early projects and events will find careers as professors, corporate executives, investors, elected officials, lawyers, and community activists. Setting the foundation for this shared vision and purpose will help us create an economic system that supports workers, investors, communities, and the environment alike—all while addressing our atmospheric carbon challenge by transforming waste carbon in the air into a valuable commodity back on the ground.

This innovation plan serves as a launchpad for the New Carbon Economy Consortium to undertake ambitious research projects in a multidisciplinary manner, facilitate the aggregation and dissemination of funding toward promising programs, and advocate for larger-scale funding for systemic research programs addressing carbon management. Following the recommendations made in this chapter, the Consortium of institutions has the necessary capacity to initiate the generation of knowledge, build scientific infrastructure, foster multidisciplinary collaboration, and create education and training programs required for the new carbon economy. The Consortium cannot accomplish these objectives alone and will need greater support and participation from research institutions, national laboratories, business, and government.

Just as putting a man on the moon required the collective efforts of many research teams across the United States and world, creating the new carbon economy will require a coordinated and distributed research effort by the New Carbon Economy Consortium. We're ready for the journey ahead, and we hope you will join us on the pathway to building a new carbon economy.

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APPENDIX

Summaries of Time Phasing of the Major Research Needs

ENGINEERED SOLUTIONS

NEXT 3 YEARS	NEXT 10 YEARS	NEXT 30 YEARS
DIRECT AIR CAPTURE		
• Develop high surface area contactors with greater reactive surface area, low capital costs, fabrication from earth-abundant material, and ready shipping and deployment • Develop efficient carbon capture materials that can be incorporated into high surface area contactors • Map high-value opportunities, including projects in locations where zero-carbon energy coincides with potential products or geological storage	• Develop ultra-low energy capture systems • Develop low-capital fabrication of DAC machinery • Integrate DAC systems with other carbon removal and utilization systems • Develop reservoir stimulation techniques that allow the use of naturally available chemical energy in key geological resources	• Develop direct ocean capture technologies, including novel CO_2 separation approaches, submersible contactors, and separation reactors • Integrate DAC into existing air-handling infrastructure of commercial and industrial buildings and in desalination plants
CO_2 CONVERSION AND USE (CO_2U)		
• Identify early "sweet spot" CO_2U opportunities with low cost, high readiness, and high impact • Expand lifecycle analysis methodologies to encompass CO_2U products • Scale up technologies for cement and concrete production (including developing feedstocks and integrated heat recovery systems) and accelerate development of standards • Scale up and reduce costs for enhanced thermal conversion of CO_2 to fuels and chemicals • Work to lower costs for CO_2U systems	• Invest in development of "clean heat" pathways for CO_2U applications (and potentially broader application) • Invest in continued development of electrical conversion pathways (electroreduction of CO_2 to hydrocarbons + alcohols) • Improve robustness and scale up electrolyzer production of syngas • Further develop chemical synthesis technologies (low- and high-temperature electrolysis, photoelectrochemistry, and solar thermochemistry) with focus on increased efficiency, yield, and selectivity and improved reactors • Develop methodologies for uniform synthesis of graphene and carbon nanotubes • Develop new methods for direct CO_2 polymerization • Integrate CO_2 utilization with existing manufacturing and energy systems	• Undertake a multiyear, sustained basic science effort to advance our understanding of the foundational physics and chemistry of materials needed in CO_2 conversion (and discovery of better materials, fabrication techniques, and mass-production technologies) • Develop new catalysts, substrates, reactors, and techno-economic assessments for photolytic conversion

ENGINEERED SOLUTIONS

NEXT 3 YEARS	NEXT 10 YEARS	NEXT 30 YEARS
ACCELERATED WEATHERING AND MINERAL CARBONATION		
• Map high-value opportunities for accelerated weathering and mineral carbonation (with a more granular representation of geological and nongeological potential feedstocks) • Undertake mine process modification and retrofits • Improve CO_2 gas-to-liquid transfer by developing technologies to enhance the supply of CO_2 from air to fluid	• Expand potential feedstocks to include human-made feedstocks (these may require additional processing, novel reactors, and better fundamental chemistry) • Begin environmental technical research and assessments for in situ and ex situ mineralization pathways • Develop new forms of mineral treatment and comminution (for example, with lasers or using waste heat) • Advance in situ mineralization that emulates natural subsurface processes	• Expand the use of accelerated weathering technologies beyond the near-surface ultramafic rock • Improve the economics and value of mineralization (for example, by recovering rare-earth elements, precious metals, and amorphous silica)

BIOLOGICAL SOLUTIONS

NEXT 3 YEARS	NEXT 10 YEARS	NEXT 30 YEARS
ECOSYSTEM RESTORATION: FORESTS, WETLANDS, RIPARIAN AREAS		
• Harmonize and improve upon existing data collection methods, analyses protocols, targeting monitoring and verification tools and their integration into predictive models • Develop high-resolution cost-effective remote sensing tools to monitor and verify carbon storage • Address gaps (diverse geographies, interactions among practices) around potential geographies, timing, and scale of forest sequestration • Decrease fire risk to protect carbon storage • Foster interdisciplinary and synthetic collaboration to align metadata standards and data science tools and assure open access to data	• Restore and monitor wetlands to track greenhouse gas dynamics across a network of field sites • Reduce the cost and increase the precision of monitoring tools • Develop decision and predictive management support tools that integrate data streams and optimize for land management outcomes that include carbon storage	• Create robust business models that rely on monitoring and verification platforms and streamline transaction costs for tracking carbon • Apply engineering approaches to develop tree cultivars that maximize carbon uptake and can grow on marginal lands, be drought-resistant, and potentially provide bioenergy feedstocks

BIOLOGICAL SOLUTIONS

NEXT 3 YEARS	NEXT 10 YEARS	NEXT 30 YEARS
SOIL CARBON SEQUESTRATION IN AGRICULTURE		
• Advance soil carbon science to improve mechanistic understanding of how carbon is stabilized in organic and inorganic forms • Build mechanistic soil carbon models based on latest science • Develop carbon monitoring and verification tools that can quickly and easily quantify, track, and verify soil carbon and handle spatial and temporal heterogeneity, including remote sensing tools • Map opportunities to increase soil carbon based on biological and physical factors • Develop a wide array of commercially available perennial crops	• Develop planning tools that include agricultural productivity, soil carbon storage, and economic sustainability of different agricultural operations • Engineer crops that can maintain or increase productivity while addressing other needs, including drought and disease resistance, carbon uptake, and perennial lifestyle • Integrate data across multiple networks and embed into a soil observatory • Innovate policy and business models to consider the implications of management practices on carbon storage	• Build a U.S.-wide soil carbon and soil biodiversity observatory and archive platform
SOIL AMENDMENTS AND NUTRIENT MANAGEMENT		
• Assess impacts of soil amendments on agricultural productivity • Determine priming effects • Quantify nutrient sequestration as a possible trade-off • Match soil amendments to local conditions in order to optimize the right amendment to the right farm or ranch • Apply lifecycle analyses to soil amendment supply chains to account for direct and indirect impacts of producing and applying soil amendments	• Apply the latest tools to discover and utilize microbes and biological communities with desirable properties, such as high carbon utilization efficiency, or develop microbial amendments for agricultural purposes • Generate big data and use computational science to model carbon storage and agricultural yields • Bring down the cost of enhancing soil carbon (including the development of soil amendments and monitoring carbon outcomes) • Analyze systems to find opportunities to match the right intervention with location and the right approach with economic outcomes	• Monitor unintended consequences of soil amendments and shifting agricultural practices beyond the traditional short-term studies (3 to 5 years)

HYBRID BIOLOGICAL AND ENGINEERED SOLUTIONS

NEXT 3 YEARS	NEXT 10 YEARS	NEXT 30 YEARS
BIOENERGY SUSTAINABILITY, CCS AND CCU		
• Develop modular systems and other approaches to distributed BECCS • Develop new sustainable biomass feedstocks • Assess coupled biogenic emissions • Utilize systems analyses to find optimal system configurations that match distributed resources with utilization opportunities	• Develop modular retrofits with carbon capture capabilities for bioenergy systems • Incorporate lifecycle, techno-economic, and ecosystem analyses to monitor sustainability impacts of bioenergy systems • Monitor biogenic emissions • Utilize advanced genetic tools to develop new bioenergy feedstocks with potential ecological co-benefits • Develop new biomass conversion processes that either have low-capital costs or create pure CO_2 streams as a byproduct • Develop CCS for modular systems	• Develop novel ways of storing biomass carbon • Evaluate indirect land use changes associated with the production of bioenergy crops • Promote regulations that create economic incentives for the production of low-carbon and, in particular, carbon-negative energy
BIOCHAR AND LONG-LIVED SOLID CARBON PRODUCTS		
• Conduct field trials that span climates, soil types, and agricultural and forestry practices • Quantify the relationship between different biochars and crop yields • Develop biochar-specific lifecycle analyses	• Set up longer-term field studies on impacts of soil amendments, such as biochar, and track their persistence in soils • Incorporate market analyses into field trials to optimize application rates across the United States • Develop new business models that link rural livelihoods with carbon removal and storage • Build distributed systems (including modular) that can produce biochar locally • Model the impact of biochar applications on soil carbon sequestration and net greenhouse gas emissions	• Assess global potential for carbon removal and storage using biochar • Develop a techno-economic analysis framework explicitly tailored to biochar

HYBRID BIOLOGICAL AND ENGINEERED SOLUTIONS

NEXT 3 YEARS	NEXT 10 YEARS	NEXT 30 YEARS
AQUATIC AND TERRESTRIAL ALGAE AND BIOPRODUCTS		
• Apply advanced genetic tools to engineer electroactive microbial communities • Select for favorable microbial community traits that increase efficiency of fuel molecule production • Tailor microbial amendments with specific traits (e.g., high C:N ratios) • Develop a cost-effective means of dewatering microalgae biomass • Integrate improved CO_2 capture and transport systems into microalgae production facilities • Map opportunities to site microalgae systems near industrial sources of CO_2 • Harness a diversity of algae to make multiple products • Find regions with sufficient water and CO_2 resources to produce and process algae-based products • Build, test, and demonstrate large-scale outdoor algae production facilities to demonstrate the scaling potential	• Build, test, and demonstrate large-scale outdoor algae production facilities to demonstrate the scaling potential	