BIOMASS CARBON REMOVAL AND STORAGE (BiCRS) ROADMAP

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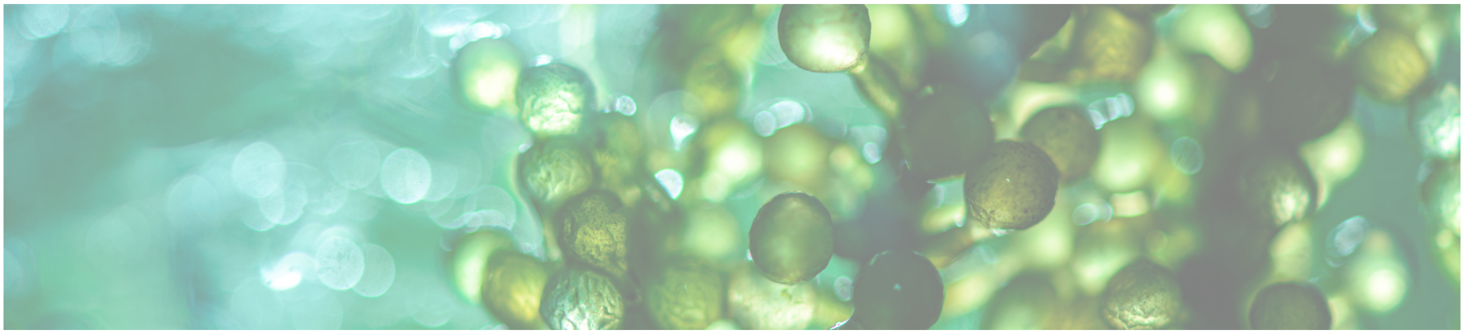

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PREFACE

This eighth ICEF roadmap tackles a challenging topic: the use of plants or algae to remove carbon dioxide (CO_2) from the atmosphere and store that CO_2 underground or in long-lived products.

Climate change experts have explored aspects of this topic for several decades. "Bioenergy with carbon capture and storage," or BECCS, has been an important part of several influential models projecting pathways to achieving the goals set forth in the Paris Agreement. Yet very few BECCS facilities exist today, and expansion plans are modest. The topic has stirred controversy due to concerns that using biomass for CO_2 removal and storage could have adverse impacts on food security, rural livelihoods, biodiversity conservation and other values.

In considering this topic, we found the existing nomenclature to be inadequate, so introduce the new term "biomass carbon removal and storage," or BiCRS. We conclude that BiCRS processes have the potential to contribute to climate change mitigation, although not at the scale assumed in some models. We believe that concerns with respect to potential adverse impacts of using biomass for CO_2 removal and storage are vitally important and must shape any vision for how BiCRS processes scale.

This roadmap builds on the body of literature produced annually in connection with the ICEF conference. Previous roadmaps have addressed:

- Industrial Heat Decarbonization (2019)
- Direct Air Capture (2018)
- Carbon Dioxide Utilization (2017 and 2016)
- Energy Storage (2017)
- Zero Energy Buildings (2016)
- Solar and Storage (2015)

As with previous roadmaps, this roadmap was released in draft form at the annual ICEF conference in early October (held virtually in 2020). Comments were received at the conference and by email in the weeks that followed.

This roadmap is a team effort. We are deeply grateful for the support provided by the ICEF Secretariat, ICEF Steering Committee (including in particular its chair, Nobuo Tanaka), the New Energy and Industrial Technology Development Organization (NEDO), experts at the Institute of Energy Economics-Japan, and our design and copy edit team (including in particular Ms. Jeannette Yusko and Dr. Kathryn Lindl).

The COVID-19 pandemic, which has shaped all our lives in the past year, underscores humanity's vulnerability to global threats. The steady accumulation of heat-trapping gases in the atmosphere is such a threat, creating risks of disruptions even greater than the terrible tragedies experienced as a result of COVID-19. However, solutions are available. The dramatic cost declines in solar and wind power in recent years offer just one example, which must be replicated across a wide range of other areas.

The ICEF Innovation Roadmap Project aims to contribute to the global dialogue about solutions to the challenge of climate change. We welcome your thoughts, reactions and suggestions.

David Sandalow
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EXECUTIVE SUMMARY

CHAPTER 1: INTRODUCTION

This roadmap introduces a new term: biomass carbon removal and storage (BiCRS). The term describes a range of processes that use plants and algae to remove carbon dioxide (CO_2) from the atmosphere and store that CO_2 underground or in long-lived products.

We started out to write a roadmap on bioenergy carbon capture and storage (BECCS). However, after analysis, we believe the term "BECCS" is too limited and has the wrong emphasis. BECCS starts with the word "bioenergy," but some processes that use biomass to remove CO_2 from the atmosphere do not involve bioenergy. Furthermore, when bioenergy is combined with carbon capture and storage (CCS), the removal of carbon from the atmosphere—not the production of energy—will often be the most valuable part of the process. (Most biomass has high carbon value but poor energy value.)

Accordingly, we introduce the new term BiCRS, which we define as a process that

(a) uses biomass to remove CO_2 from the atmosphere,

(b) stores that CO_2 underground or in long-lived products, and

(c) does no damage to—and ideally promotes—food security, rural livelihoods, biodiversity conservation and other important values.

The use of biomass for climate mitigation has generated controversy for many years. Advocates have argued that strategies such as avoided deforestation, afforestation and BECCS could provide multiple benefits, including cheap emissions reductions, low-cost removal of CO_2 from the atmosphere, biodiversity conservation and sustainable livelihoods. Critics have highlighted risks, including competition with food resources, adverse impacts on rural communities, slowing the steps needed to transition from fossil fuels, and indirect land-use change reducing or eliminating claimed climate benefits.

Three principles have guided our approach to BiCRS:

- First, do no harm.
- Second, social acceptability is key to BiCRS' success.
- Third, technology development should reflect social priorities.

CHAPTER 2: BACKGROUND

The idea of combining bioenergy with CCS was first proposed roughly 20 years ago. BECCS was featured prominently in several integrated assessment models in advance of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2014) and IPCC 1.5 °C Report (2018). Unfortunately several models allocated very large and unrealistic amounts of carbon removal to BECCS.

Relatively few commercial-scale facilities that use biomass to sequester carbon underground or in long-lived products are in operation today. We estimate ~2.5 Mt/y of CO_2 is currently sequestered by such facilities, with as much as 25 $MtCO_2$/y in planning or development. This is 1000-2000 times smaller than BiCRS' 2.5-5.0 $GtCO_2$/y potential.

While these facilities sequester carbon, they may or may not meet the standards for a BiCRS facility: doing no damage to—and ideally promoting—food security, rural livelihoods, biodiversity conservation and other important values.

Under reasonable assumptions, the value of using biomass for removing carbon from the atmosphere may exceed the value of using biomass for energy. (The authors have labeled this the "Aines Principle," after our co-author Roger Aines who first proposed it.) This observation suggests the need for a paradigm shift in thinking about the optimal uses of biomass resources.

CHAPTER 3: BiCRS – RATIONALE AND RISKS

Removing CO_2 from the air and oceans is necessary to meet global climate goals. The scale of the endeavor—more than 10 billion tCO_2/y by mid-century—is daunting.

Three major approaches have been proposed for removing CO_2 from the atmosphere: (1) natural solutions (forests, soils and wetlands), (2) engineered methods to directly remove CO_2 from the air (such as direct air capture), and (3) hybrid approaches (such as BiCRS). We believe all three approaches will be needed in the decades ahead. If properly developed, regulated and monitored, BiRCS could contribute many gigatons of carbon removal while promoting economic development around the world.

However some types of biomass production—including some dedicated energy crops—can damage ecosystems, hurt local farmers and increase global carbon emissions. To be successful, biomass conversion for carbon removal must prevent harm to ecosystems, generate economic returns, and ensure removal of carbon from the atmosphere taking account of indirect land-use effects.

CHAPTER 4: BIOMASS FEEDSTOCKS

Potential sources of biomass for BiCRS include the following:

- Waste biomass including agricultural wastes, forestry wastes, black liquor from paper production and municipal solid wastes. Waste biomass is the most desirable type of feedstock for BiCRS due to it low cost, low environmental impact and low impact on food and fiber production.
- Dedicated energy crops including sugar cane, corn, rapeseed, palm oil and soya, as well as woody biomass such as willow, eucalyptus, poplar and pine.
- Microalgae, typically cultivated on land, in ponds or in reactors.
- Macroalgae (seaweed) grown in oceans or lakes.

Previous work has analyzed annual global biomass availability for biofuel production. Based on this work and our own analysis, we find roughly 2.5 to 5.0 $GtCO_2/y$ could be removed from the atmosphere and stored by 2050 using biomass produced with minimal environmental impact.

CHAPTER 5: TRANSPORT

Biomass can be transported by truck, rail or ship. The products of biomass conversion (such as ethanol, hydrogen or captured CO_2) can also be transported by truck, rail or ship and, in some cases, by pipeline. The current structure of global trade in bioenergy is based on moving processed biomass (mainly wood pellets and bioethanol) to a final conversion facility near the location where energy services will be consumed.

BiCRS could operate differently: conversion facilities could be located near the source of biomass feedstock, with little biomass traded globally. The CO_2 captured during conversion could be stored underground near the conversion facility, with the carbon removal benefits sold to global buyers based on widely agreed upon accounting and sustainability standards. The energy services or products resulting from the biomass conversion could be used locally or sold in global markets.

CHAPTER 6: CONVERSION PROCESSES

Biomass conversion is generally divided into biochemical and thermochemical pathways. Biochemical pathways rely on living microorganisms—often yeast or bacteria—to process biomass into more useful forms. Thermochemical pathways involve controlled heating and decomposition of biomass. The optimal conversion technology in any situation depends in part upon the type of feedstock. The technical maturity of different conversion pathways varies widely.

CHAPTER 7: CARBON SEPARATION AND STORAGE

To achieve true net-zero emissions, carbon removed from below the Earth's surface by burning fossil fuels must be balanced by returning carbon below the Earth's surface or by storing carbon in long-lived products.

A number of carbon removal methods rely on storing CO_2 in plants. Although storage of CO_2 in plants can be cheap and produce ecosystem benefits, the duration of such storage is short, the risk of release is high and the potential is limited. In contrast, the capacity of the Earth's crust for durable storage of CO_2 is effectively limitless. Conventional geological storage systems like saline formations have an estimated storage volume of 10-20 trillion tons—far more than either annual emissions or total historic emissions.

One of the most promising aspects of BiCRS is the potential for co-location of large biomass supplies and geological storage resources, particularly where they naturally occur in close proximity to each other. Several geographies—including the southeast and central US, California, Alberta, southeast Asia and the North Sea—have high potential for both biomass production and CO_2 storage.

CO_2 can also be stored in a number of long-lived products, including concrete, durable carbon, biochar and long-lived wood products. The capacity of these products to durably store CO_2 is far less than the capacity of the Earth's crust.

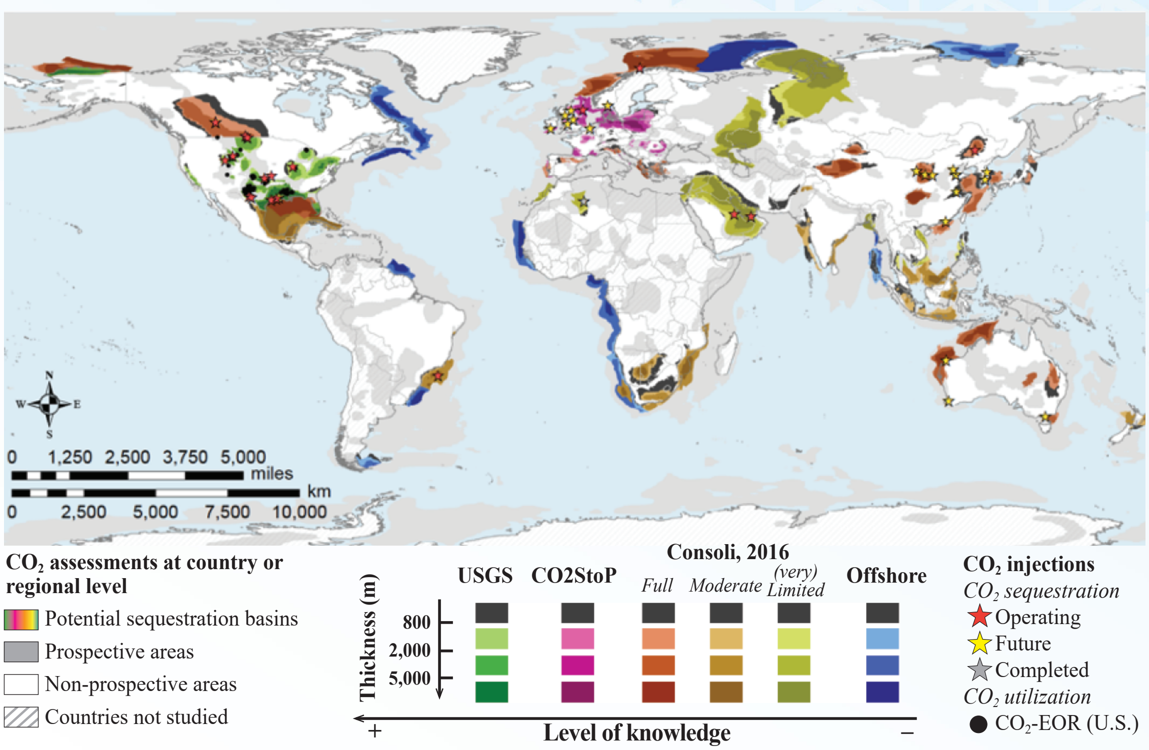


Figure ES.1. *Distribution of conventional CO_2 storage worldwide. NOTE: Some areas are not fully explored and characterized. Source: Kolosz and Wilcox, 2020*[1]

CHAPTER 8: RESEARCH AGENDA

A. Technology

Many BiCRS processes that produce energy are relatively advanced and well understood. In comparison, many pathways that do not produce energy are under-explored. Biomass can be used to produce hydrogen, fuels and chemicals, with CO_2 emissions captured and stored. Engineered wood products, bioliquid injection, macroalgae abyssal dispatch and biofiber entombment are new concepts that need to be evaluated.

Any large-scale implementation will require careful monitoring of land use/land cover (LULC) in all locations that provide biomass. LULC change can be monitored in a variety of ways, but the most effective approach is to use satellite-based remote sensing, which allows global coverage and relatively high precision.

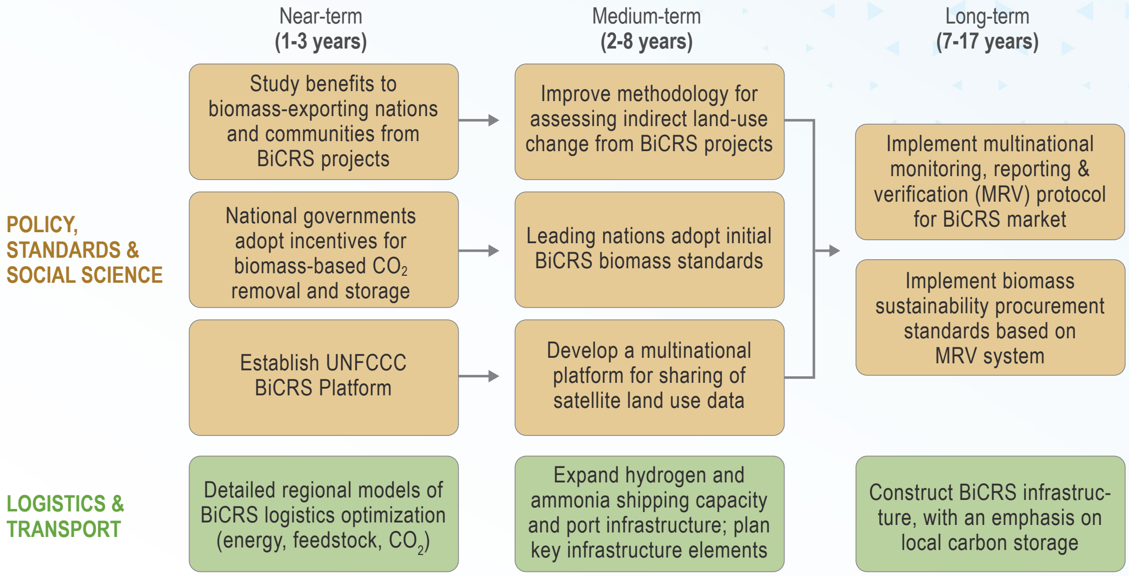
While significant research attention has been paid to developing crops optimized for energy production, far less research attention has been paid to developing crops optimized for life-cycle carbon removal. Such a "carbon-optimized" plant could be part of a BiCRS system that achieves far higher carbon removal rates than a system using wastes or even conventional dedicated energy crops.

B. Social Science

Very large-scale deployment of BiCRS could affect food security, clean energy development, biodiversity, water resources and other services of value to society. Addressing the relationship between these topics will require social science research drawing from a number of disciplines including economics, political science and sociology, as well as related fields including agronomy, nutrition, hydrology and engineering.

C. Integrated Analyses

Integrated analyses addressing both technology and social science issues will be required for BiCRS to scale. Techno-economic assessment, which addresses both technology and economic issues, is one of the most familiar forms of this type of analysis. In addition, life-cycle greenhouse emissions analyses will be especially important as BiCRS scales.



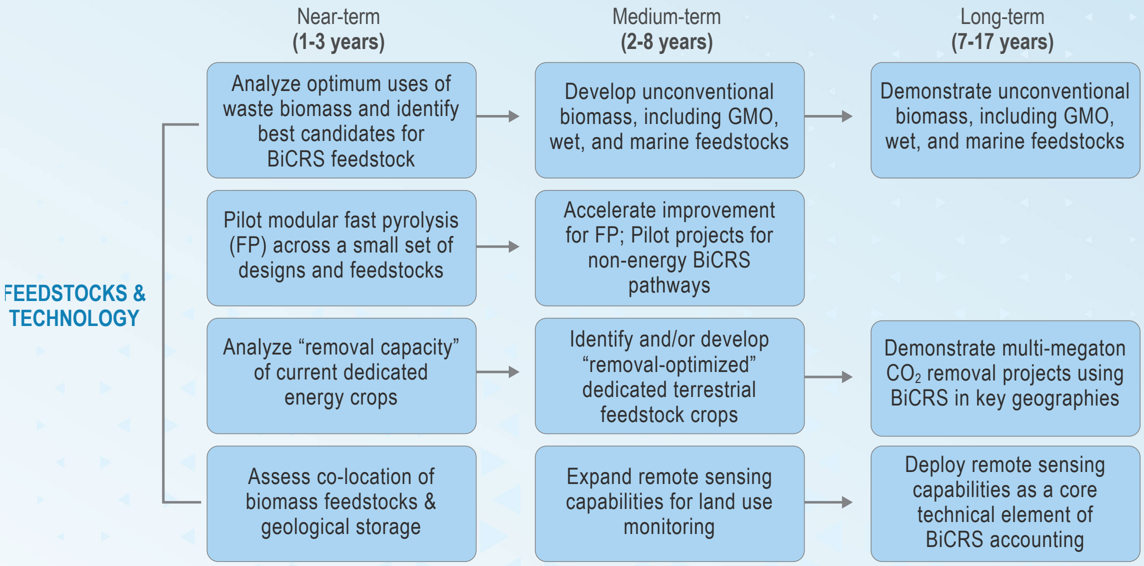


Figure ES.2. *Innovation Roadmap – Biomass Carbon Removal and Storage (BiCRS)*

CHAPTER 9: POLICY

A. Incentives for Removing Carbon from the Atmosphere

There are small private markets for CO_2 removed from the atmosphere, including for enhanced oil recovery (EOR) and voluntary CO_2 offsets, yet these are far too small for BiCRS to scale. Government policies to provide incentives for carbon removal are essential. Available tools include emissions trading programs, tax mechanisms and mandates.

B. Support for Development and Deployment

BiCRS facilities are large and capital intensive. First-of-a-kind BiCRS facilities are unlikely to be able to attract private capital in amounts sufficient for initial deployment. Governments play a central role in supporting deployment of such projects. Government support for deployment can take several forms, including tax incentives, grants, loan guarantees, revenue enhancements and procurement preferences.

C. Standard-Setting

BiCRS projects raise challenging issues with respect to measuring, monitoring and crediting of carbon removal. These issues involve a complex interplay of scientific, technical, socio-economic and institutional factors.

Measuring the life-cycle emissions of a BiCRS project is essential. This process is mostly similar to lifecycle measurements for other projects, although it becomes more complicated when energy crops or timber are used as feedstocks. Complications arise because the use of land to grow energy crops or timber for BiCRS projects may lead to clearing of forests—where the energy crops or timber are grown (direct land-use change) or in distant places (indirect land-use change)—offsetting the emissions benefits associated with the BiCRS project.

One critical issue is the time frame in which to measure carbon neutrality. If timber is burned and takes 40 years to grow back, is that process carbon neutral? How should the risk of forest fires or other forest loss during those 40 years be addressed?

Crediting for carbon removal can create some conceptual challenges, especially when biomass is being shipped internationally to a BiCRS facility. Which country should receive the credit for the carbon removal? Which should be charged for any emissions related to harvesting the feedstock?

Developing standards in these areas will be a multi-year process. The UN Framework Convention on Climate Change (UNFCCC) could create a BiCRS platform similar to its REDD+ Platform as a venue for international dialogue and standard-setting related to BiCRS.

CHAPTER 10: FINDING AND RECOMMENDATIONS

FINDING 1:

Several gigatons of CO_2 could be removed from the atmosphere and stored underground or in long-lived products each year using biomass produced with minimal environmental impacts.

FINDING 2:

Energy production is not the only way that biomass can be used in combination with carbon capture to store CO_2 underground or in long-lived products.

FINDING 3:

Governance and accounting issues are key challenges to BiCRS and may set its practical limits.

FINDING 4:

The carbon removal value of biomass may increasingly exceed its energy value.

FINDING 5:

Many technologies and practices required for BiCRS are already mature.

FINDING 6:

Launch a BiCRS Platform modeled after its REDD+ Platform as a global venue for this dialogue.

FINDING 7:

Without proper governance and standards, BiCRS could be counterproductive with respect to climate mitigation, biodiversity conservation, food security and rural livelihoods.

Recommendation 1:

We introduce a new term—biomass carbon removal and storage (BiCRS). We recommend adoption of this term and the approach it reflects in considering the potential role of biomass in achieving net-zero global greenhouse gas emissions.

Recommendation 2:

We recommend that development of BiCRS technologies and projects focus first on waste biomass.

Recommendation 3:

We recommend a framework in which projects start with the guiding principle “Do no harm.”

Recommendation 4:

We recommend an innovation roadmap for BiCRS, focusing on hydrogen, fast pyrolysis and selected non-energy pathways.

Recommendation 5:

We recommend a targeted effort to develop monitoring, reporting and verification (MRV) for BiCRS.

Recommendation 6:

We recommend a set of nations and companies lead development of the frameworks, methodologies and standards that must underlie gigaton-scale BiCRS as an industry.

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1 Kolosz, B. and Wilcox, J. (eds), 2020 (in press), A primer on Carbon Dioxide Removal.

CHAPTER 1:

INTRODUCTION

A New Term: Biomass Carbon Removal and Storage (BiCRS).

This roadmap introduces a new term: biomass carbon removal and storage (BiCRS). The term describes a range of processes that use plants and algae to remove carbon dioxide (CO_2) from the atmosphere and store that CO_2 underground or in long-lived products. These processes have the potential to contribute to the vital goal of reaching net-zero emissions of heat-trapping gases globally by mid-century.

We started out to write a roadmap on bioenergy carbon capture and storage (BECCS). That term is commonly used for most of the processes we describe. BECCS has been part of the dialogue on climate change mitigation for several decades and plays an important role in many integrated assessment models that explore pathways to net-zero emissions. Today a handful of facilities around the world have deployed BECCS processes.

However, after analysis, we believe the term "BECCS" is too limited and has the wrong emphasis. BECCS starts with "bioenergy," implying that energy production is the most important part of processes that use biomass to capture and store CO_2. But that is not always the case. Indeed in some instances—such as using biochar to improve soil fertility—biomass can be used to capture and store carbon without energy production. And even when bioenergy production is coupled with carbon capture and storage (CCS), the removal of carbon from the atmosphere—not the production of energy—will often be the most valuable part of the process. (Most biomass has poor energy value but high carbon value.) Thus we start by asking "How can biomass best be used for removal of carbon from the atmosphere and storage of that carbon for the long-term?," introducing the term "biomass carbon removal and storage" or "BiCRS."

This question immediately raises others. Experience during the past several decades suggests important questions about the extent to whWich biomass can be used to help fight climate change without reducing cropland, hurting rural livelihoods or threatening biodiversity. So the full question we ask is "How can biomass best be used for removal of carbon from the atmosphere and storage of that carbon for the long-term without damaging—and ideally while promoting—food security, rural livelihoods, biodiversity conservation and other important values?"

We therefore define BiCRS as a process that:

(a) uses biomass to remove CO_2 from the atmosphere,

(b) stores that CO_2 underground or in long-lived products, and

(c) does no damage to—and ideally promotes—food security, rural livelihoods, biodiversity conservation and other important values.

Our analysis suggests that BiCRS processes could capture and store 2.5-5.0 gigatons of CO_2 annually ($GtCO_2$/y) by mid-century. Although this figure is more modest than those used in some integrated assessment models for BECCS (which range as high as 20 $GtCO_2$/y), BiCRS could be an important part of global efforts to achieve net-zero emissions in the decades ahead.

Yet much work remains to achieve CO_2 capture and storage of 2.5-5.0 gigatons per year. Some of this work is technological. Cost reductions in a number of technology pathways for capturing and storing carbon would help BiCRS scale. The harder work, however, is likely to be institutional and political. For BiCRS to reach its full potential, new institutional arrangements and broad consensus among a wide range of stakeholders would be required.

This roadmap explores these issues. We start by offering an ideal vision of what BiCRS might look like in midcentury. We then provide background, including a short history of the role of BECCS in the global climate dialogue, list of related facilities currently in operation and comparison of the value of using biomass for carbon removal with the value of using biomass for energy production. In Chapter 3, we discuss the rationale for and risks of BiCRS. Chapters 4-7 address a number of core issues with respect to BiCRS, including biomass availability, transport, conversion processes, and CO_2 separation and storage. Chapter 8 describes a research agenda and Chapter 9 explores policy issues that will be central to BiCRS' ability to scale. In Chapter 10, we offer findings and recommendations.

B. BiCRS 2050: An Ideal Vision

What could BiCRS look like in 2050? We offer the following ideal vision—a speech that could perhaps be delivered that year.

UN Framework Convention on Climate Change

55th Conference of the Parties (COP 55)
December 2050

Address of the President,
Biomass Carbon Removal and Storage (BiCRS) Coalition

At this conference, we are celebrating the world achieving net-zero greenhouse gas emissions—a goal many once thought impossible. Today, let us also celebrate the important role that biomass carbon removal and storage (BiCRS) is playing in the world achieving that goal.

Many people know very little about BiCRS. Let me explain how BiCRS removes several billion tons of carbon dioxide (CO_2) from the atmosphere each year—a number that will grow in the years ahead.

Three decades ago, when I began my career, many people thought this was impossible. They thought that biomass feedstocks could not be produced at a scale sufficient to make a difference in climate mitigation. They thought biomass production for carbon removal would lead indirectly to destruction of tropical forests and increases in food prices. They thought transportation of biomass to processing facilities on a mass scale was impractical without significant carbon emissions. They thought programs for crediting countries with emissions reductions related to BiCRS would be too complicated and prone to manipulation.

But we have overcome these challenges.

We start with the sustainable production of biomass. This comes from many sources:

- Wastes and residues
- Dedicated carbon-removal crops
- Managed forests
- Microalgae
- Seaweed/macroalgae
- Agricultural wastes in California, sustainably managed plantations in Canada and Indonesia, and seaweed in Japan's Exclusive Economic Zone are just some of the leading examples of sustainable sources of biomass.

Production of this biomass contributes to local livelihoods and economies, with careful attention to protecting social and environmental values. After harvest, the biomass is shipped to conversion facilities. Because carbon removal is a core goal, we are rigorous about ensuring that CO_2 emissions associated with shipping are zero or close to zero. That means co-locating carbon removal facilities with the biomass source where feasible. It means using zero-carbon fuels for transporting biomass when co-location is not feasible. (These zero-carbon fuels include green hydrogen, the primary fuel for long-distance marine shipping around the world today.) Many organizations help track the harvesting and transport of biomass, sharing data to ensure that harvested land is sustainably replanted and natural ecosystems remain undisturbed.

Once biomass arrives at conversion facilities, the carbon it contains is converted thermochemically, biochemically or through combustion. Some of these facilities make products with commercial value. These products include fuels that were once made with coal, oil and gas, helping displace emissions that might otherwise come from the combustion of fossil fuels. Other products include power, heat, construction materials and biochar.

As a final step, CO_2 at these facilities is either captured and pumped underground for permanent geologic storage or converted into long-lasting products in which the carbon is trapped for decades or centuries.

None of this would be possible without some key building blocks.

- Incentives for carbon removal in national legislation through carbon pricing, regulatory standards and other policy tools
- Widely-recognized international standards for sustainable production of biomass, including land-use change constraints and ecosystem protections
- Satellite monitoring of forests globally to provide transparency and help evaluate whether biomass is being sustainably managed
- A global agreement on crediting of biomass removal when biomass is grown in one country and its CO_2 is stored in another country

How did we get here?

Several advances during the 2020s were key to BiCRS' success. These advances included widespread adoption of international standards for sustainable biomass use, enabled by improvements in satellite monitoring to track land-use change and enable tree-indexed carbon quantification for the first time. Technical advances allowing cheap production of microalgae on land and macroalgae in the oceans played an important role as well. Expanded hydrogen transportation and use in industrial processes was another important factor. The harmonized accounting systems for biomass removal and storage introduced by several leading accounting firms and later adopted by UNEP was also key.

However it was in the early 2030s that BiCRS really began to reach maturity. The seven largest biomass-buying nations met with the seven largest biomass-producing nations to develop the Global Sustainable Biomass Standards. That club of 14 nations set the rules for sustainable harvesting, accounting systems for local CO_2 storage, and carbon intensity standards of key goods traded on exchanges around the world. Core elements included the ban on harvesting primary forests for BiCRS, the ban on harvesting peat-forests for BiCRS and the Biomass/Biodiversity Compact, highlighting the high priority all BiCRS stakeholders attach to protecting wildlife and biodiversity.

Today millions of BiCRS certificates trade on exchanges around the world daily. And BiCRS is contributing to local economies, promoting the just treatment of indigenous peoples, and helping protect ecosystems around the world—while also helping the world achieve net-zero emissions of heat-trapping gases. I hope you're all proud of the role you've played in making this a reality.

And these programs have not just helped clean up the atmosphere, they have created good jobs in rural areas, empowering land-owners to use their land to benefit the environment. Today collectives of small farmers and ranchers can decide whether to sell their biomass around the world or create BiRCS facilities locally and sell the credits for the same benefit.

Worldwide monitoring of these biomass markets ensures that they are helpful to both the local environment and the local population, cutting off crediting when this is not the case. Wastes are no longer burned in open fires or allowed to decay to methane-rich gases, turning additional agricultural material into value. And the energy products produced are either carbon neutral or carbon negative. Moreover, global trade in biomass and carbon dioxide removal (CDR) credits has allowed many developing nations of the world to benefit financially from contributing to the fight against climate change.

The most important part of our path to this point was when we agreed that CO_2 removal must begin with consideration of preventing harm to ecosystems, enabling good governance at the local and the global level, ensuring energy and economic returns, and understanding the stocks and flows of biological systems. With these worldwide understandings and constraints, biomass has become a powerful contributor to the mitigation of climate change and general increase of world welfare.

But our work is not done. In the years ahead let us continue to find ways for BiCRS to contribute to the fight against climate change while contributing to rural livelihoods, promoting food security and protecting biological diversity. The planet's atmosphere, ecosystems and economies can be brought into harmony if we continue the good work we have begun.

C. Guiding Principles

The use of biomass for climate mitigation has generated controversy for many years.[1] Advocates have argued that strategies such as avoided deforestation, afforestation and BECCS could provide multiple benefits, including cheap emissions reductions, low-cost removal of CO_2 from the atmosphere, biodiversity conservation and sustainable livelihoods. Critics have highlighted risks, including competition with food resources, adverse impacts on rural communities (see Eco-colonialism box), slowing the steps needed to transition from fossil fuels, and indirect land-use change reducing or eliminating claimed climate benefits.

In preparing this document, we have been mindful of this ongoing dialogue. In particular, we have been mindful of the fact that large-scale implementation of BiCRS could raise many of the concerns cited above. In considering approaches to BiCRS, we have been guided by three principles that we commend to others considering these topics as well:

First, do no harm. We support application of a precautionary principle in scaling up BiCRS. If a project threatens food security, rural livelihoods or biodiversity conservation, for example, it does not qualify as a BiCRS project and should not be pursued.

Second, social acceptability is key to BiCRS' success. Without support and demand from a wide range of stakeholders, BiCRS processes will not and should not reach significant scale.

Third, technology development should reflect social priorities. Technologies should not be pursued for their own sake, but in the context of the social situations in which they will be deployed. In particular, these technologies should actively contribute to achieving the economic and social goals of the communities who are most impacted by their installation and operation.

We believe BiCRS has considerable potential to contribute to the fight against climate change if these three principles are followed.

1 Carton, Wim, Adeniyi Asiyanbi, Silke Beck, Holly J. Buck, and Jens F. Lund. "Negative Emissions and the Long History of Carbon Removal." *WIREs Climate Change* (August 2020) at p. e671 (https://onlinelibrary.wiley.com/doi/full/10.1002/wcc.671).

CHAPTER 2: BACKGROUND

A. A Short History of BECCS in the Global Climate Dialogue

In 2001, Michael Obersteiner and Kenneth Mollersten published an article in *Science* arguing that

> "biomass energy can be used both to produce carbon neutral energy carriers, *e.g.*, electricity and hydrogen, and at the same time offer a permanent CO_2 sink by capturing carbon from the biomass at the conversion facility and permanently storing it in geological formations…"[1]

David Keith made a similar point in a commentary in *Climatic Change* the same year.[2] In the years that followed, BECCS as a concept for CO_2 removal and energy production had adherents (*e.g.*, Williams, 1998[3]; Socolow and Pacala, 2004[4]) but largely remained a marginal option.

BECCS' role in the global climate dialogue changed between 2012 and 2017 for two reasons. First, BECCS grew in global prominence with the ribbon cutting of the first commercial-scale BECCS facility—the Archer Daniels Midland project in Decatur, Illinois.[5] This facility gathered byproduct CO_2 from fermentation and stored roughly 1 million tons CO_2 per year ($MtCO_2$/y) in a deep saline formation. With the commissioning and safe operation of this plant, capture and storage of carbon from biomass was no longer a hypothetical option but, rather, a viable functioning approach with well understood costs for at least one case.

Second, BECCS featured prominently in integrated assessment models (IAMs) associated with deep decarbonization, especially in advance of the Intergovernmental Panel on Climate Change (IPCC) 2014 and 1.5 °C reports (*e.g.*, Minx *et al.*, 2017[6]). The inclusion of BECCS was partly due to the fact that the computational modules needed to represent both bioenergy and CCS already existed in many IAMs, making it easy to add BECCS to the modeling framework. This ease of implementation in the analytical models meant that BECCS soon became the primary pathway for carbon removal in IAMs.[7]

Unfortunately, many models allocated very large and unrealistic volumes of carbon removal to BECCS (see Muratori *et al.*, 2016[8]). Many studies responded to this artificial inflation of BECCS by explaining why BECCS alone would face enormous challenges managing 10 $GtCO_2$/y removal (*e.g.*, Gough *et al.*, 2018[9]). The initial (and problematic) forecasted role for BECCS has led to broad discussion of what would actually constitute reasonable, appropriate and ethical biomass conversion and CO_2 removal.

Today, there is no consensus view on this question and many uncertainties remain concerning both technical and governance issues. One key dimension of these discussions is the physical and ecological limit of biomass production, but other equally important dimensions include macroeconomic questions around the relative value of energy from biomass, concerns regarding ecosystem degradation risk, the potential impacts on communities that are now or would be harvesting biomass, consequences for food and fiber availability and costs, and a host of related concerns. Our concept of BiCRS shares many similarities with BECCS but is designed to respond to the important concerns and constraints that have been realized since Obersteiner and Mollersten's 2001 article. In some situations this requires a ground-up reimagination of biomass-based CO_2 removal and storage systems, while in others only minor tweaks are required.

B. Biogenic CO_2 Sequestration Facilities Today

Relatively few commercial-scale facilities that sequester biogenic carbon are in operation today. We estimate ~2.5 $MtCO_2$/y of biogenic carbon is currently sequestered each year by such facilities, with as much as 25 $MtCO_2$/y in planning or development (Table 2.1). We note that 2.5 $MtCO_2$/y is 1000-2000 times smaller than BiCRS' 2.5-5.0 $GtCO_2$/y potential (see Chapter 4).

To our knowledge, the only nation with a comprehensive plan for implementing true negative emissions through biomass-based processes is Sweden.[10] That plan outlines how Sweden's forest resources can be used in BiCRS-type processes to achieve 1.8 $MtCO_2$/y of negative emissions by 2030 and 3-10 $MtCO_2$/y by 2045.

Facilities that currently sequester biogenic carbon include several ethanol plants in the US, where federal and many state policies provide support, as well as

Conversion Technology	Existing Negative Emissions [$MtCO_2$/yr]	Planned Negative Emissions [$MtCO_2$/yr]	Number of Companies
Combustion w/CCS	1.2	16	3 (1 biomass, 2 municipal solid waste [MSW])
Gasification-to-fuels w/CCS	n/a	6	(3 biomass, 1 MSW)
Ethanol w/ CCS	1.3	2.1	3
Pyrolysis w/ bio-oil CCS	0.01	Unknown	1
Biochar	0.01	Unknown	Unknown

Table 2.1. *Summary of existing and planned capacity for sequestration of biogenic carbon*

several waste-to-energy plants in northern Europe, where burning municipal solid waste to produce electricity is a mature industry. (Municipal solid waste [MSW] in Europe typically contains 60-80% paper, yard waste or food waste.[11]) In addition, several very small facilities use pyrolysis with bio-oils and CCS, and others produce biochar for use in soils. The Drax power station in the UK, which burns wood pellets imported from the US, is currently piloting carbon capture and plans to sequester CO_2 underground in the future (Table 2.2).

While these facilities sequester biogenic carbon, they may or may not meet the standards for a BiCRS facility (doing no damage to—and ideally promoting—food security, rural livelihoods, biodiversity conservation and other important values).

C. Relative Value of Carbon Removal and Energy from Biomass

BiCRS processes use biomass to provide an environmental service—the removal of CO_2 from the atmosphere and storage of that carbon below the Earth's surface or in long-lived products. In the dialogue around BECCS, that environmental service has mostly been thought of as incidental to the production of energy using biomass. However, under reasonable assumptions, the value of using biomass for removing carbon from the atmosphere may exceed the value of using biomass for energy. (The authors have labeled this the "Aines Principle," after our co-author Roger Aines who first proposed it.) This observation suggests the need for a paradigm shift in thinking about the optimal uses of biomass resources.

To illustrate this, we note that one oven-dry ton (odt) of biomass contains approximately 18 GJ of energy. It also contains approximately 0.5 tons of carbon (biomass is roughly half carbon by weight), which is equivalent to 1.8 tons of CO_2.[12] In Figure 2.1, we show the value of the CO_2 contained in a ton of biomass for a range of potential CO_2 prices (expressed as US dollars per ton of CO_2 or $/t$CO_2$), as well as the value of the energy contained in a ton of biomass. To estimate the energy value, we use the value of 18 GJ of natural gas, crude oil, steam coal and wood pellet feedstock (the "energy content equivalent value"). This analysis shows the following:

- Above a carbon price of approximately 25 $/t$CO_2$, the carbon content of biomass is more valuable than the equivalent energy content of bituminous steam coal (at 60 $/ton) and wood pellet feedstock (at 30 $/ton)
- Above a carbon price of approximately 35 $/t$CO_2$, the carbon content of biomass is more valuable than the equivalent energy content of natural gas (at 4 $/MMBtu)
- Above a carbon price of approximately 65 $/t$CO_2$, the carbon content of biomass is more valuable than the equivalent energy content of crude oil (at 40 $/barrel)

Both carbon and energy prices vary significantly by jurisdiction and over time.[13] However, carbon prices are likely to rise in the future. As political and ecological pressure mounts, the economic value of CO_2 removal will continue to grow. Although there is no long-term futures market for CO_2 removal, it is reasonable to anticipate that the market value of CO_2 removal will increase in the next decade. If that happens, the carbon-removal value of biomass may increasingly exceed its energy value. This implies that biomass used in processes that sequester carbon may be more valuable for this environmental service than for any energy services it provides.

Analysts have used a number of approaches to estimate the current value of a ton of carbon removal:

Company/ Project Name	Technology	Project Status	Currently Storing CO_2	Country	Feedstock	Primary Product	Capacity for Major Product	Geologic Sequestration at Scale [$MtCO_2$/yr]
Drax	Combustion with geologic sequestration	Pilot, full-scale announced	No	England	Wood	Electricty	2.6 GWe	16
Twence	Combustion with geologic sequestration	Pilot	No	Netherlands	Municipal solid waste (MSW)	Electricty & heat	405 GWhe, 1.5 PJ heat	0.042
Fortum Oslo Varme	Combustion with geologic sequestration	Full-scale demonstration	No	Norway	Municipal solid waste (MSW)	Electricty & heat	10.5 MWe, 55 MW heat	0.2
Archer Daniels Midland	Ethanol with geologic sequestration	Operational	Yes	US	Corn	Corn ethanol	300 Mgal/yr	1
Arkalon	Ethanol with enhanced oil recovery	Operational	Yes	US	Corn	Corn ethanol	110 Mgal/yr	0.17
Bonanza	Ethanol with enhanced oil recovery	Operational	Yes	US	Corn	Corn ethanol	55 Mgal/yr	0.1
White Energy Plainview	Ethanol with enhanced oil recovery	In planning	No	US	Corn	Corn ethanol	120 Mgal/yr	0.342
White Energy Hereford	Ethanol with enhanced oil recovery	In planning	No	US	Corn	Corn ethanol	120 Mgal/yr	0.342

Table 2.2. *Existing facilities with capture and/or geologic sequestration of biogenic CO_2*

- **Social cost of carbon:** This is perhaps the most common approach. Due to the enormous range of input assumptions about future climate damage, estimates vary widely (from \$1/ton to at least \$10,000/ton[14]).
- **Compared to other options:** Another approach compares CO_2 removal to other mitigation options, either through integrated assessment models of global economic systems[15] or through estimation of global marginal abatement costs.[16,17]
- **What markets will bear:** In carbon markets such as the California carbon offset market and the European Trading Scheme, the weighted average price of carbon is in the range of \$20-\$21 per ton.[18] Within the CA Low Carbon Fuel Standard, current CO_2 abatement prices trade at \$150-200/ton, although these must be monetized through a fuel sold in California. Prior and existing climate policies provide an enormous range of value by technology option, including subsidies well in excess of \$1000/ton.[19]
- **What companies will pay:** Early actions by some companies reveal a demand for CO_2 removal services. In particular, some tech companies, power companies and industrial manufacturers have made commitments to net-zero emissions and have overtly included CO_2 removal in their estimates. Some have expressed a willingness to pay above-market prices to stimulate technology development and deployment.[20] For comparison, the internal carbon prices (shadow prices) announced by companies range from \$40-80/ton.

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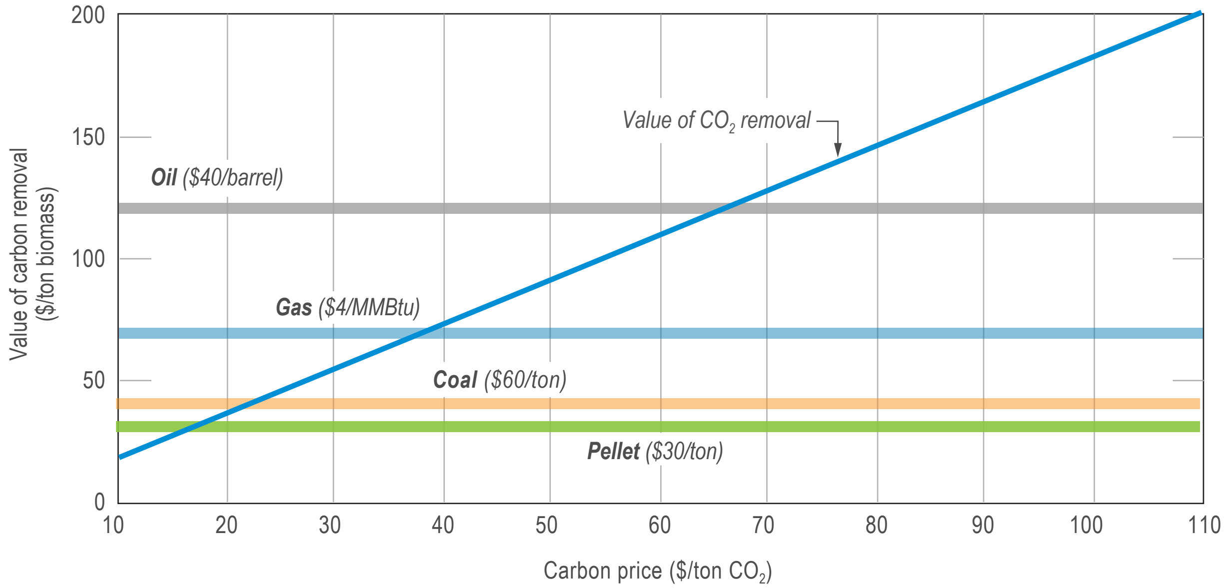

Figure 2.1. *Comparison of the carbon-removal value of biomass with the energy content equivalent value of biomass for a range of carbon prices. Natural gas value: 4 $/MMBtu; crude oil value: 40 $/barrel; steam coal (bituminous) value: 60 $/ton; wood pellet feedstock: 30 $/ton.*

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CHAPTER 3:

BiCRS – RATIONALE AND RISKS

A. Rationale for BiCRS

Removing CO_2 from the air and oceans is necessary to meet global climate goals. The scale of the endeavor is daunting. According to the Intergovernmental Panel on Climate Change (IPCC), "All pathways that limit global warming to 1.5 °C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100-1000 $GtCO_2$ over the 21st century."[1]

Three major approaches for removing CO_2 from the atmosphere have been proposed: (1) natural solutions (forests, soils and wetlands), (2) engineered methods to directly remove CO_2 from the air (such as direct air capture), and (3) hybrid approaches (such as BiCRS). All three require significant investment and development for the world to meet agreed climate change targets.

In this report, we provide a roadmap for using biomass to remove carbon from the atmosphere at scale and store it for the long-term. Because of the historical importance of modern bioenergy, electricity has been an early focus of the literature in this field. However, if the goal is to remove CO_2 from the air and store it long-term, the focus should be on maximizing the carbon removed from the air while minimizing costs and promoting other beneficial activities. As discussed above, we call this approach biomass carbon removal and storage (BiCRS), to emphasize that the goal is not to use biomass to create energy (particularly given the plunging costs of solar and wind energy) but as a means to take advantage of the very efficient system of capturing CO_2 that nature has provided with carbon-based biomass. Our goal is to take advantage of that system in an appropriate way, providing carbon removal and long-term storage of biogenic carbon.

We believe all three approaches to carbon removal will be needed in the decades ahead. A balance of cost, societal factors, environmental impacts and land use must be considered for each approach, with the ultimate degree of usage depending on this balance. For instance, natural solutions have environmental and social benefits that may far outweigh the relatively low costs but are often limited by land availability. Direct air capture will likely be the most expensive approach but can be deployed at almost unlimited scale. There are no easy solutions for cleaning up the excess CO_2 in the air. All available and imagined methods have costs, benefits and limitations.

Hybrid approaches fall between the other two in terms of cost and have substantial advantages and risks. They have significant potential today because many methods for collecting and converting biomass are well-established. (Methods for capturing and storing the CO_2 need more attention.) This is one reason why the relatively simple concept of BECCS has gotten so much attention. Through farming, forestry and waste management, the world generates large volumes of waste biomass that could immediately be used as a source of carbon storage. Much of this waste biomass is a problem today, either because it is burned or landfilled, where it emits methane as well as CO_2.

BiCRS processes affect the carbon cycle through conversion of biomass and storage of biogenic carbon in geologic reservoirs or long-lived products. Among engineered carbon removal options, BiCRS offers the dual benefit of decreasing the flow of geologic carbon to the atmosphere through substitution for fossil fuels and increasing the flow of atmospheric carbon into long-term storage. Some BiCRS processes offer additional value from energy and fuels production or conversion of biomass into biochar, construction materials or other durable products. Other BiCRS processes directly store biomass for long periods of time without additional benefit.

If properly developed, regulated and monitored, BiRCS could contribute many gigatons of carbon removal while promoting economic development around the world. This could proceed in three stages:

1. Application of existing technology to waste biomass widely available around the world. Some of this will be done in advance of the development of widely-accepted standards and will inform those standards.
2. Development of improved technologies and widely-accepted standards for the use of biomass as a climate mitigation tool, providing confidence that biomass-based approaches can be effective and appropriate.

- Development of new economic models in which biomass is harvested without adverse impacts and either (a) processed locally with sale of credits that represent true removal of CO_2 from the air or (b) traded to provide feedstock for carbon removal, as well as hydrogen, fuels, power and other products in industries that improve the quality of the atmosphere instead of degrading it.

B. Risks of BiCRS

Production of some types of biomass—including some dedicated energy crops—can damage ecosystems, hurt local farmers and increase global carbon emissions. Policies to promote such production can have significant negative impacts. Critics have argued that US ethanol policy (and EU biodiesel policy), for example, have contributed to deforestation and had little if any positive impact on global carbon emissions.[2]

Successful deployment of biomass conversion for carbon removal must begin by preventing harm to ecosystems, ensuring economic returns, and delivering net carbon removal from the atmosphere. For biomass conversion to serve carbon removal needs, avoiding a set of potential failure modes is essential. Examples of potential failure modes to be avoided include the following:

- **Damage to ecosystems.** Biomass cultivation for carbon removal could damage productive and diverse ecosystems on land or in the oceans. Possible outcomes include replacement of diverse ecosystems with monocultures, long-term losses of carrying capacity or productivity, infestations, fires, and degradation of water and soil. Integrated environmental assessment models will be an important tool for evaluating potential damage.
- **No CO_2 removal benefit.** While it is possible to cultivate biomass for carbon removal so that the life-cycle emissions are negative, that result is not guaranteed. A poor understanding of emissions in the biomass life-cycle—including in particular the implications of indirect land-use change—and flawed implementation could lead to biomass conversion projects resulting in a net increase of CO_2 emissions.
- **Adverse impacts on food security.** Biomass conversion projects could compete with food production for arable land, increasing food prices and adversely affecting food security for vulnerable populations.
- **Eco-colonialism.** (See box 3–1.)

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1 IPCC, Global Warming of 1.5 °C: Summary for Policy Makers (2018) at p.19, htp://report.ipcc.ch/sr15/pdf/ sr15_spm_ fnal.pdf.

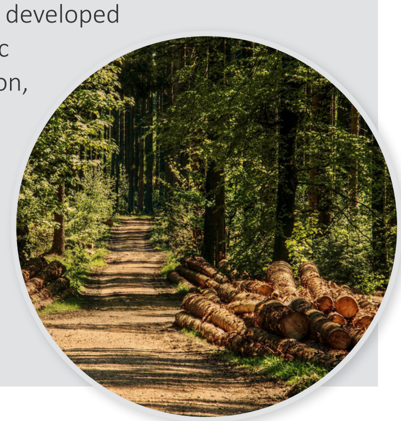
2 Bicalho, Tereza, Cécile Bessou, and Sergio A. Pacca. "Land Use Change within EU Sustainability Criteria for Biofuels: The Case of Oil Palm Expansion in the Brazilian Amazon." *Renewable Energy* 89 (April 2016) at p. 588-97 (https://www.sciencedirect.com/science/article/abs/pii/S096014811530522X?via%3Dihub).

BOX 3-1 Eco-colonialism

Colonialism is the domination of one people by another, typically involving the domination of people in developing countries by those in developed countries. Eco-colonialism is a type of colonialism in which the natural resources in developing countries are appropriated for the benefit of those in developed countries—often without meaningful consent by those who live near the resources. The impacts of eco-colonialism have included the following:

- Lasting damage to natural resources (forests, soils, water)
- Unsustainable practices, leading to ecosystem collapse
- Political corruption, specifically associated with natural resource extraction
- Unfair labor practices and deep systemic inequality
- Lasting negative health effects on local populations
- Local environmental degradation (e.g., to air and water quality)
- Disregard to local impacts on population or indigenous industries
- Permanent loss of biodiversity

The global growth of BiCRS could lead to the risk of eco-colonialism, which must be addressed carefully and thoughtfully. Exports of biomass from developing to developed nations creates risks of exploitation, damage to habitats and ecosystems, and the impacts listed above. These risks are present even if developed countries purchase biomass to help remove CO_2 from the atmosphere—a global public good. Many communities in developing countries would benefit from climate mitigation, but the damages they suffer from exploitive resource acquisition practices may outweigh those benefits. Standards and procedures are needed to prevent these harms.



Similar scenarios have occurred in nations including Indonesia, as developed nations' demand for palm oil and timber has led to environmental destruction, loss of biodiversity, corruption of rule of law and increased emissions. Congolese and Amazon forests face similar challenges today. As BiCRS processes scale, careful attention to risks related to eco-colonialism will be essential.

CHAPTER 4:

BIOMASS FEEDSTOCKS

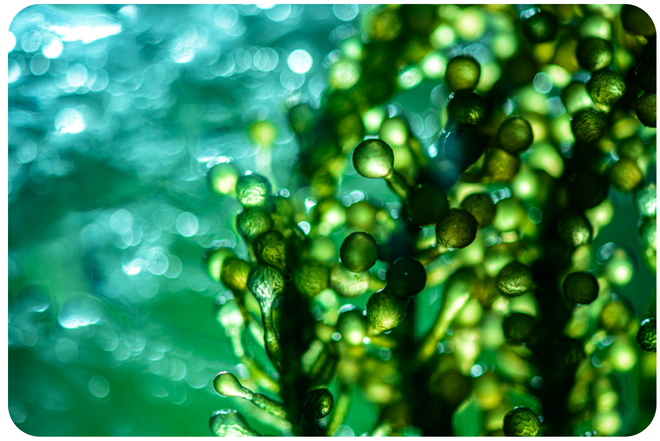
The sources of biomass that could be used for BiCRS are largely the same as for conventional bioenergy systems. Broadly, these sources fall into the following categories:

Murasawa, Naoharu & Koseki, Hiroshi & Iwata, Yusaku & Sakamoto, Takabumi. (2018). Eval. the Fires and O_2 Def. Risks Caused by Stored Ag. Waste. Sustainability. 10. 1116. 10.3390/su10041116.

- **Waste biomass:** Many forms of biomass are considered waste, meaning they have low to negative costs of production and do not affect the availability of biomass for food and fiber applications. These biomass sources include agricultural wastes (such as crop residues, mill waste, grain hulls, *etc.*), forestry wastes (thinnings and logging residues, as well as standing dead biomass resulting from tree die-off events[1]), black liquor from paper production and municipal solid wastes (MSW). As much as 3.3 Gt of agricultural wastes are produced each year, and their disposal poses a growing problem, particularly because they are often left in the field to decompose, releasing methane (a potent greenhouse gas), or they are burned, producing particulates and other air pollutants.[2,3] Using waste biomass as the primary source of feedstock for BiCRS is highly desirable because of its low cost, low impact on food and fiber production, and potential to help address these problems. However, waste biomass could also be used for other important purposes, including low-emissions construction materials[2] and some forms of nutrient recovery[4,5] and soil improvement.[6] These alternative uses must be considered when evaluating the overall benefits from using waste biomass as a BiCRS feedstock since they represent an opportunity cost and may in some cases provide a greater positive climate impact.

- **Dedicated crops.** Agricultural land can be used to produce short-rotation crops dedicated to energy uses (usually known as energy crops). These crops—including sugar cane, corn, rapeseed, palm oil and soya—are grown today in large quantities and are in widespread use as biofuel feedstocks. Longer-rotation woody biomass sources are also available, including willow, eucalyptus, poplar and pine. Creating plantations for these crops at the expense of existing forests is generally counterproductive in terms of carbon emissions and other values. Similarly, expecting these crops to grow on existing agricultural lands is usually counterproductive since this can lead to displacement of crops into unspoiled ecosystems and spikes in food costs. However, dedicated crops as BiCRS feedstocks may have a role in the case of abandoned or degraded land where their cultivation would not compete with food and fiber production or displace natural ecosystems. This is why estimates of the potential biomass available as feedstock for BiCRS are primarily constrained by agricultural land availability for food and fiber production, although biomass production on non-arable land may ease these constraints. No substantial research has addressed the question of which crops maximize carbon removal in the context of BiCRS, and conventional energy crops may not actually be optimal as BiCRS feedstocks.

- **Forestry.** The forestry industry spans the globe, with annual revenues of $270 billion derived from 2.4 billion hectares of productive forest land (about 60% of the world's forests).[7] The industry has grown 86% since 2000; much of that growth is in roundwood, sawnwood, wood panels and wood pellets (all relevant to biomass conversion and removal).[8] Total volumes are roughly 5 billion cubic meters or about 2 gigatons oven-dry mass.[9] In some nations, forests represent both a large fraction of trade and revenues and an important source of jobs for rural and poor communities. Existing global forestry supply chains could in principle be used to provide forest-derived biomass as feedstock for BiCRS, although there are significant risks related to sustainability and carbon storage as noted in Chapter 3 above. Indeed, one of the fastest-growing bioenergy pathways today is the use of wood pellets combusted for power generation and heat, although the climate impacts of this pathway continue to be debated.[10]



- **Microalgae.** Biomass can be produced from various strains of microalgae cultivated on land, in ponds or in reactors, including *Chlorella sorokiniana* and *Nannochloropsis salina*. These sources of biomass are relatively expensive using current technology and require substantially more infrastructure; processing steps (*e.g.*, dewatering) are also very different from conventional biomass processing. In addition, growing these microalgae requires land area, although not necessarily in highly productive locations. These biomass sources offer an extremely efficient way to convert sunlight into biomass, which is why they have been extensively researched.[11-13]

- **Macroalgae.** Biomass can be harvested from macroalgae (seaweed) grown in the oceans or lakes. This is appealing because of the absence of competitive pressures on land and freshwater resources. However, technology to cultivate macroalgae at large scales in the ocean is immature, and transporting and processing this biomass presents challenges. Achieving economic feasibility will require technology advancements and significant increase in scale, which carries some ecological risk.[14-19]

An important overall question in evaluating the potential of BiCRS is the global amount of biomass feedstock that could reasonably be made available for this use. While no such comprehensive estimates have been made for BiCRS, a range of analogous estimates have been made for biofuels and/or BECCS. These estimates are primarily projections to a future date (usually 2050) and are constrained by avoiding or minimizing the pressure put on global food and fiber supply through land competition. Therefore, these estimates rely on a set of assumptions about future global diet (both quantity and preferences around meat consumption), future crop productivity gains and future land availability, among others. Because of the inherent uncertainties in these projections, firm estimates are not possible, but it is possible to describe the range of estimates and the sets of assumptions that influence them.

Quantification of Available Biomass on the Basis of Capturable Carbon

Quantifying biomass on a common basis requires choosing a form of measurement that can be applied to different biomass types. Because most estimates of global biomass availability have been developed in the context of bioenergy, they are expressed in terms of the energy content of biomass (*i.e.*, EJ). In what follows, we convert these estimates into the total amount of carbon (or CO_2) that could be captured and stored from this biomass.

Arriving at this value requires two steps: (1) estimating the total amount of biomass feedstock that could be made available for BiCRS (usually as fully de-watered "oven-dry tons" or odt) and (2) estimating the fraction of carbon in that biomass that could be captured and stored by a BiCRS process. While the former can be easily determined from bioenergy studies (because 1 odt of biomass contains 18 GJ of energy on average[20]), the latter is more complex. An important simplifying assumption is that most biomass is approximately 50% carbon by mass.[20]

The first major route for biomass use in BiCRS systems is combustion to generate power and heat. The combustion process results in 100% of the carbon in the combusted biomass being converted to CO_2 in dilute form in flue gas (which is also true for creation of hydrogen, the most efficient transport fuel use). This CO_2 can in principle be captured with high efficiency (over 90%) but the associated energy consumption leads to emissions, as does harvesting, de-watering, transportation and other supply chain steps. These emissions must be subtracted from the gross amount of carbon captured from the combusted biomass to arrive at a net result. A conservative lower limit is that 50% of the original carbon in the combusted biomass can be captured and stored on a net basis[20] (based on miscanthus grown in Brazil and burned for power in Britain). Given the 50% carbon content of biomass, this estimate implies 0.25 net tons of carbon (0.91 tCO_2) could be captured and removed per 1.0 odt of biomass through the combustion route.

The second major route for biomass use in BiCRS systems is through fermentation, gasification, pyrolysis or related processes to produce liquid fuels and other products. This route has two important differences from the combustion route. The first is that a smaller fraction of the carbon content of the biomass feedstock is converted to CO_2 because a significant portion of the carbon winds up in the fuel or other products. (This carbon is later converted to unabated CO_2 emissions when it is used as transportation fuel). However, the CO_2 produced during the conversion is purer than the CO_2 produced in the combustion process and therefore requires less energy to capture. These factors, as well as the emissions associated with harvesting, de-watering, transporting and other supply chain steps as noted above, imply that approximately 25% of the original carbon in the converted biomass can be captured and stored on a net basis.[21] This estimate in turn implies that 0.125 net tons of carbon (0.45 tCO_2) could be captured and removed per odt of biomass through the liquid fuel route.

Estimates of Future Global Biomass Availability

Slade *et al*. summarize over 120 estimates of annual global biomass availability made by a range of authors, grouping these estimates into categories and identifying assumptions that lead to different results.[22] Assumptions consistent with biomass production having minimal environmental impacts yield estimates of up 100 EJ of energy content, which corresponds to 5.5 Gt of biomass (oven-dry) by 2050. In light of the analysis above indicating that 0.45 to 0.91 tCO_2 can be captured per 1 odt of biomass, we find a maximum of 2.5 to 5.0 $GtCO_2$/y could be captured and stored by 2050 using biomass that can be produced with minimal environmental impact.

This finding is based on several conservative assumptions including that agricultural productivity gains will be small, meat consumption will continue to grow and food demand will stay high. Under these assumptions, very little high-quality land will be available for growth of energy crops, which will therefore be restricted to marginal or degraded land. The studies on which this finding is based generally identify a large share of biomass feedstocks coming from agricultural residues, forest residues and other wastes (industrial, municipal and manure). Forestry contributes little. The finding aligns well with the US National Academy of Sciences' recent estimate of the potential global carbon removal rate from BECCS (3.5 to 5.2 $GtCO_2$/y).[23]

In light of the estimates summarized by Slade *et al.*[22] and the US National Academies study, we find 2.5 to 5.0 $GtCO_2$/y to be a reasonable estimate of the potential for BiCRS.

We find the higher estimates for biomass availability summarized by Slade *et al.*[22] to be optimistic at best because of their assumptions concerning land-use change and high agricultural productivity gains. Without substantial technology improvements in productivity and/or biomass conversion, these amounts are highly unlikely to be achieved. The extended range of estimates of annual biomass availability summarized by Slade *et al.* is 5.5 to 16.5 Gt (oven-dry) by 2050 (corresponding to 100 to 300 EJ of energy content). This implies a range of 2.5 to 15 $GtCO_2$/y that could be captured and stored if all this biomass were available for BiCRS.

These estimates assume that crop productivity gains will match increased food demand from population growth and increased meat consumption. In these scenarios, approximately 100 to 500 Mha of land is available for growing energy crops, which is mostly grassland or degraded, marginal or deforested land (currently 4800 Mha of land globally is classified as agricultural[24]; see Figure 4.1). The contribution from waste (industrial, municipal and manure) is higher than the low-range scenarios, and in some cases these scenarios envision substantial reduction of global forest cover or intentional replacement of mature forest with younger, faster-growing forest.[22]

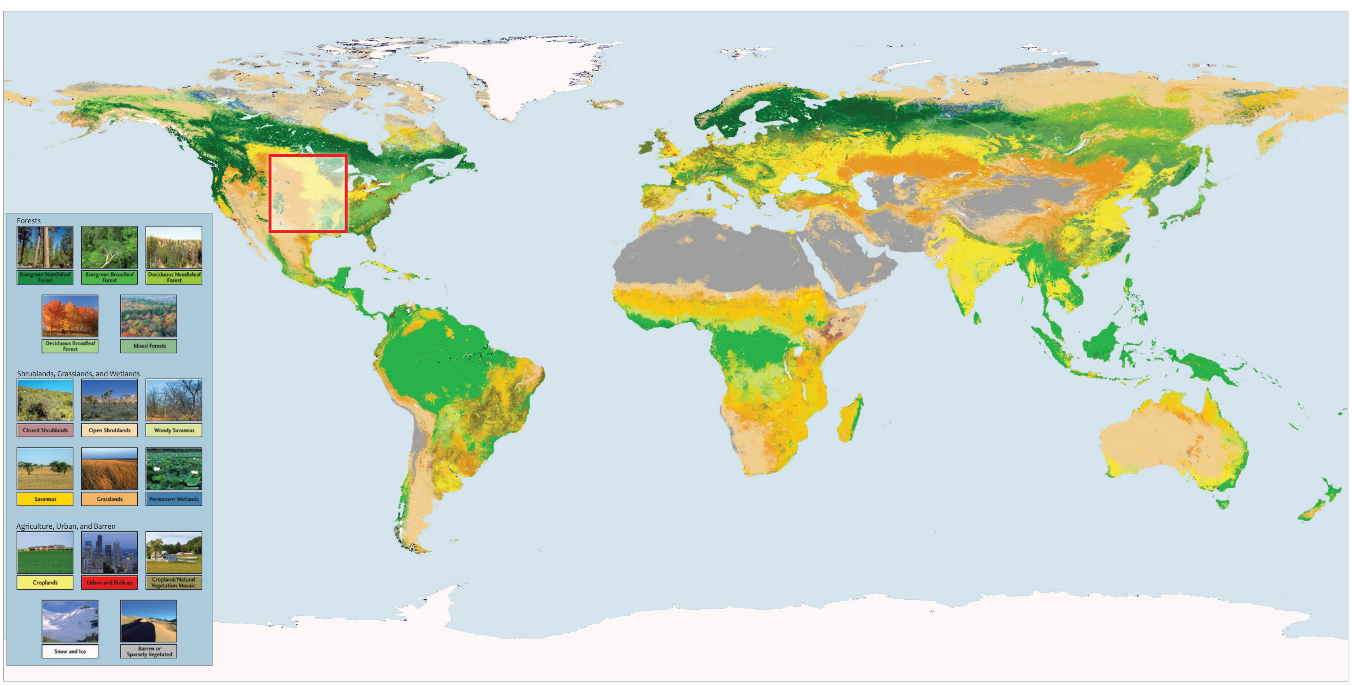


Figure 4.1. *Global land surface cover by category. The red box covers approximately 500 Mha, the higher end of the area envisioned for dedicated energy crop production in the extended biomass availability scenarios. Image: NASA GSFC and Boston University*[25].

A limited number of extreme projections of annual biomass availability estimate that more than 16.5 Gt (oven-dry) of biomass will be available by 2050 (corresponding to over 300 EJ of energy content, which approaches current primary global energy consumption). Because of the assumptions that underlie these estimates, we deem them extremely unrealistic and exclude them from further consideration.[22] These assumptions include productivity gains outpacing food demand and areas of 1000 Mha or larger (the size of China) becoming available for energy crops. Up to 10% of global land mass would be dedicated to energy-related biomass production in these scenarios. High-meat diets would be possible only with extensive deforestation.

Several additional factors are important to consider when attempting to understand these scenarios. First, efforts to improve crop productivity often focus on yields in just three crops (wheat, rice and maize), which provide over 40% of global food calorie supply.[26] Most scenarios assume a relatively inelastic global food demand for these and other crops, which would mean that productivity gains translate into agricultural land freed from food production and thus usable for energy crops. However, evidence supporting these scenarios is scant, and crop intensification may simply lead to greater food demand and little to no land sparing (rebound effect).[27,28] Additionally, intensifying agricultural productivity may run into fundamental limits of sustainability without major efforts to maintain soil quality.[29]

Second, water constraints are poorly understood. Most biomass availability scenarios assume energy crops would be rain-fed rather than irrigated, but water availability may still limit productivity. Important progress has been made in improving water-use efficiency without compromising yield in model transgenic organisms,[30] and a range of possible engineered redesigns to plant systems to improve yield has been proposed.[31] However, a full understanding of this issue at the system level is lacking, and the availability of land to grow large amounts of energy crops may not be sufficient for their actual production if these water constraints prove to be severe. In a similar vein, the optimal crops and related tradeoffs with intensification and diversification for BiCRS may not necessarily be the same as those for energy crops, an issue that deserves further study.[32]

Third, the emissions associated with biomass logistics (conversion and transport), as well as the specific choice of route for BiCRS, remain poorly understood. In a scenario under which biomass is transported long distances by emissions-intensive means, the net carbon available for capture and storage by either the combustion or liquid-fuel route are about half of the original potential of the biomass. Further, the emissions associated with compression, transport and injection of captured CO_2 may be larger than assumed here, depending on the actual location of at-scale biomass conversion facilities and CO_2 pipelines. All these considerations underscore the importance of system-level analysis to accurately understand the net emissions and potential for carbon removal from any form of BiCRS.

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CHAPTER 5:

TRANSPORT

Biomass can be transported by truck, rail or ship. The products of biomass conversion (such as ethanol, hydrogen or captured CO_2) can also be transported by truck, rail or ship and, in some cases, by pipeline. The optimal approach to transport logistics is highly dependent on a variety of factors, including the locations of biomass production, CO_2 storage and product use; the type, number and size of conversion facilities; and the costs and availability of transport modes and pipelines. This chapter will address general considerations for how these factors influence the optimal approach to BiCRS feedstock and product transportation.

In general, it is undesirable to transport biomass in raw form for more than a short distance. Several types of preprocessing can be used to improve transportation efficiency and provide "conversion-ready" feedstock from otherwise highly varied sources. These preprocessing methods include drying, chipping, sorting, fractionating, sizing, leaching and densifying, which can be done relatively close to the point of harvest/collection.[1] Preprocessed biomass can then be further upgraded—such as with wood pellet manufacture—or delivered directly to conversion facilities, resulting in a variety of products (see below), as well as captured CO_2. CO_2 is best transported as a liquid, which can be in refrigerated form on trucks or rail cars (although the latter is rare) at relatively low pressure (approximately –40 °C and 20 bar) or at ambient temperature in pipelines at high pressure (80 to 140 bar).

In the US, truck transport of biomass has an average cost of \$0.159/t-mile, while truck transport of liquid CO_2 has an average cost of \$0.175/t-mile. In both cases, the associated fuel CO_2 emissions value is 88 g/t-mile (2025 projected value for the US). Rail transport of biomass has an average cost of \$0.071/t-mile; rail cost of CO_2 is harder to estimate given its rarity but is approximately \$0.071/t-CO_2-mile with an additional cost of \$2/t-CO_2 for staging and interconnection equipment. CO_2 pipeline costs depend strongly on volume but are generally lower than all other options for flow rates above 2000 tons/day.[2]

Transporting both biomass and CO_2 by ship is possible, although the latter is only practiced today in very small volumes. Ship transport is of particular importance for large-scale BiCRS scenarios because many countries lack sufficient land area to cultivate biomass at scale and would likely look to import it, potentially over long distances by sea.[3] BiCRS does not generally envision long-distance (>1000 km) transport of CO_2 by ship since local utilization and geological storage are preferable. However, scenarios for 800-km CO_2 ship transportation have been developed with costs ranging from 19 to 36 euros/tonne.[4]

International Trade in Wood Pellets and Bioethanol

Currently, international trade in biomass products related to energy is dominated by wood pellets (for power generation and heating) and bioethanol (as liquid transportation fuels).

In 2018, more than 2 million tons of wood pellets were shipped globally, a 21% increase over 2017. US exports grew 50% year-over-year, with almost all going to the UK, Belgium and Denmark for use in power generation, heating and related uses. While the EU remains the largest global market for wood pellets,[5] demand in Japan and South Korea doubled from 2016 to 2018,[6] with Japanese demand primarily sourced from Canada and Vietnam.[7-9] Shipping costs between the ports of Savannah, USA and Rotterdam, Netherlands are estimated at 12 to 20 euros/ton.[10] (See Figure 5.1.)

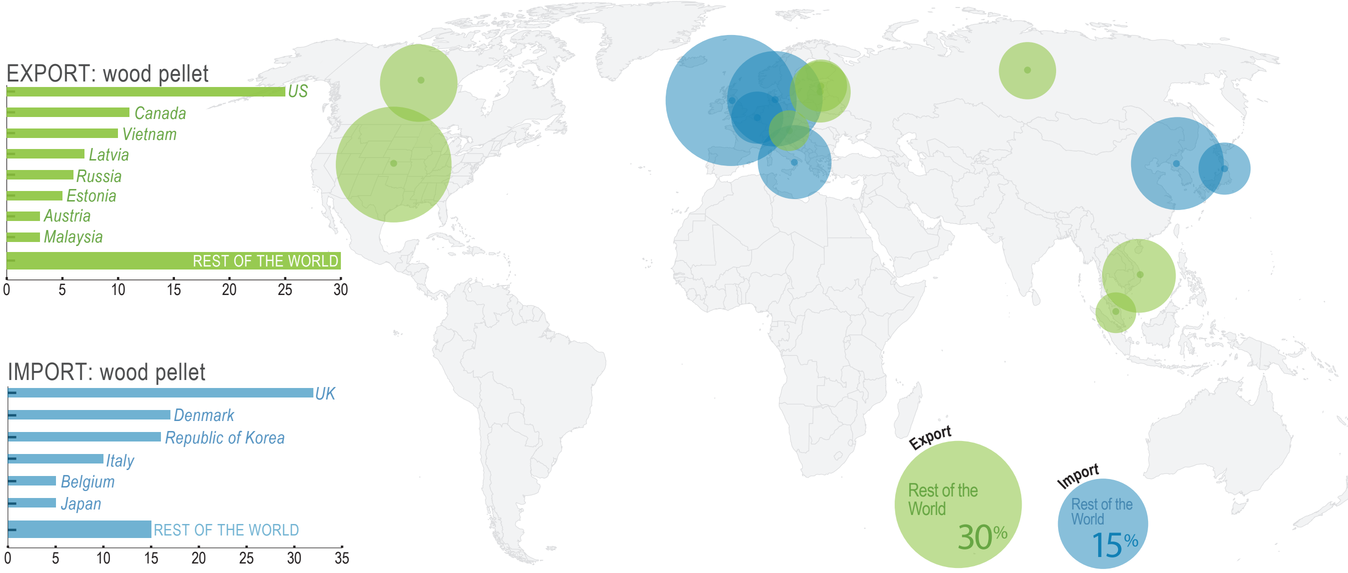

Figure 5.1. *Global exports and imports of wood pellets in 2018 by market share percentage. The total volume of wood pellet global trade was approximately 20 million tonnes. Source: FAO Forestry database11; Chart: LLNL.*

Transportation of wood pellets involves several logistical complications that are not present for other bulk cargoes. Pellets must be protected from moisture and kept temperature-controlled due to their ability to self-heat and ignite.[12] Pellets also degrade and release carbon monoxide during transit, which can pose a hazard to crew.[13] Many import terminals are not currently capable of providing this handling above a limited scale and will require upgrades to handle expected growth in volume.[14] These issues are complicated by efforts to increase the loading of ships transporting wood pellets; Panamax-class vessels are used to carry over 60,000 tons of wood pellets at a time.[15]

Global production and export of bioethanol is dominated by the US and Brazil. From 2017 to 2019, US annual exports averaged 5.9 billion liters and Brazilian annual exports totaled 1.7 billion liters, representing 70% of all exports (see Figure 5.2).[16] Import restrictions, some based on assessments of the emissions associated with bioethanol production, have somewhat limited this trade.[17] While bioethanol requires special handling as a flammable liquid, it is similar to conventional hydrocarbon shipment and thus more compatible with existing logistics infrastructure. Shipping costs vary by major route; for the east-bound trans-Atlantic route from the US, they are $50 to $88/tonne; for the US Gulf Coast to Asia route, they are $60 to $98/ton; and for the US Gulf Coast to Brazil route, they are $75 to $85/tonne.[18,19]

Given these factors, a significant expansion of international biomass shipment for the purpose of BiCRS would involve several features/challenges:

- Biomass must be processed before long-distance transportation to improve economics and to standardize cargo for logistics and handling. The current standard formats are solid wood pellets and liquid bioethanol, and significant investment has been made in infrastructure to handle these formats. Approaches to BiCRS that rely on large-scale biomass shipment may therefore seek to use biomass in these formats. If other formats prove to be preferable, this could involve increased infrastructure costs. An important exception may be pyrolysis oil (also known as bio-oil, see Box 7-1), given its compatibility with petroleum transportation infrastructure.
- In the case of wood pellets and bioethanol, global trade is dominated by a small number of producers/exporters and a slightly larger number of consumers/importers. This means a relatively small number of ports are involved, with a limited set of shipping routes representing the majority of trade volume. At the scales anticipated in the future, biomass trade for BiCRS may significantly increase the ports and routes involved, requiring corresponding infrastructure investments.

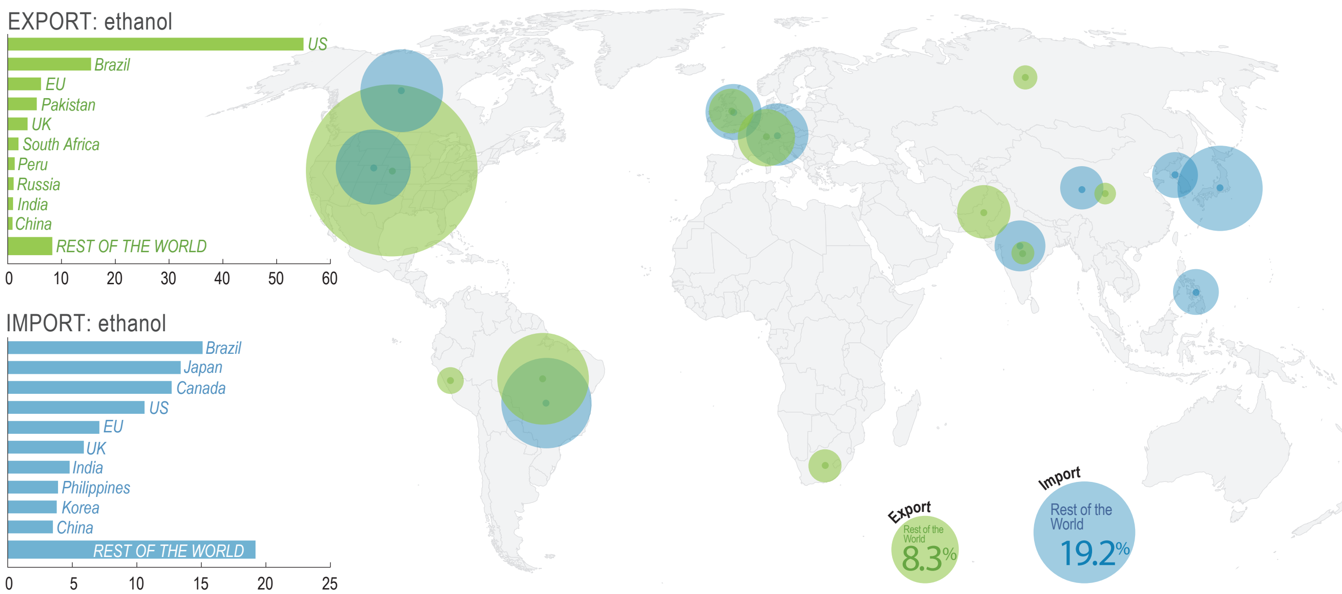

Figure 5.2. *Global exports and imports of ethanol (average value 2017 to 2019) by market share percentage. The total volume of ethanol global trade is approximately 17 billion liters (equivalent to 13.4 million tonnes). Source: OECD, Table C.40.2.20 Chart: LLNL.*

Alternatives to Biomass Shipment

The current structure of global trade in bioenergy is based on moving processed biomass to a final conversion facility near the location where energy services will be consumed. For wood pellets, this facility is usually a power plant or district heating system. For biofuels, the facility is usually fuel distribution infrastructure near vehicles.

BiCRS could operate differently: conversion facilities could be located near the source of biomass feedstock, with very little biomass traded globally. The CO_2 captured during conversion could be stored underground near the conversion facility, with the carbon removal benefits sold to global buyers based on widely agreed upon accounting and sustainability standards. The energy services or products resulting from the biomass conversion could be used locally or sold in global markets.

Such a logistics paradigm would emphasize the creation of jobs and economic value near the biomass source, rather than treating the biomass as a commodity export. This could create significant economic opportunities for communities near sources of biomass. (Today biomass feedstock for wood pellets is valued at approximately 30 $/ton, while finished wood pellets sell for approximately 170 $/ton.[10]) Such a logistics paradigm could also help insulate communities and biomass-exporting nations from commodity price volatility, which has a number of negative impacts, including large budget deficits when commodity prices fall and large exchange rate fluctuations due to capital movement. (Today about two-thirds of developing countries are commodity-dependent, meaning that at least 60% of their export earnings are from commodities.) BiCRS conversion facilities located near biomass feedstock production regions could contribute to economic development and protect local economies from commodity price swings.[21]

One strategy for achieving this vision would be to convert biomass to hydrogen or ammonia at facilities located near both the biomass feedstock source and CO_2 storage sites. The resulting hydrogen or ammonia could be used domestically or sold on global markets. Today, this scenario is strongly constrained by the lack of viable, low-cost shipping of hydrogen. (The first liquified hydrogen container ship was launched by Kawasaki in 2019.[22]) Shipment of liquified ammonia has a longer history, including attention in Southeast Asia,[23] and may serve as an alternative approach.[24] Although the scale of the global shipping fleet is still relatively small,[25] many existing vessels could be retrofitted for ammonia fuel or simply for transportation and regasification.[26] If long-distance transport of hydrogen or ammonia becomes economically viable, it could enable local biomass conversion and CO_2 storage, with significant economic benefits for biomass-producing regions.

Lessons from palm oil

Palm oil and palm kernel oil are highly valued edible oils extracted from the flesh and seed of the oil palm tree. They form an important part of global trade in processed biomass; the oils are primarily used in the food and beverage sector, but approximately 10% is used in biofuel production.[27] Approximately three-quarters of global production is exported, with imports reaching nearly 47 million tons in 2017.[28] Production is dominated by Indonesia and Malaysia, which accounted for 85-90% of global production in 2016.[27]

The growth of the global palm oil market offers several cautionary lessons for BiCRS. First, policy-driven biofuel subsidies in the European Union were among the factors that helped lead to the rapid growth of palm oil production.[29] This growth has been accompanied by widespread deforestation as land was cleared for plantations: between 2001 and 2015, oil palm replaced 10.5 million hectares of forest globally,[30] and over 50% of all deforestation on the island of Borneo between 2005 and 2015 was associated with palm oil production.[27]

The European Commission recently recognized this deforestation impact and excluded palm-oil-based biodiesel from eligibility for meeting renewable transportation goals, envisioning a full phase-out of palm oil biodiesel by 2030.[31] This belated realization of the full environmental damage associated with palm oil production suggests that a better understanding of the full life-cycle impacts should have been developed before the original policy frameworks were put in place. **In scaling up BiCRS, it will be important to fully understand the life-cycle environmental impacts of biomass feedstocks before enacting significant policy support.**

A second lesson relates to the challenges of establishing credible, effective sustainability certifications for biomass cultivation at scale. Despite the fact that the European Commission called for biofuel certification schemes to prevent deforestation over a decade ago,[32] these schemes have had limited effectiveness. The most notable scheme for palm oil production, the Roundtable on Sustainable Palm Oil (RSPO) cofounded by the World Wildlife Fund, has faced numerous criticisms including a slow pace of adoption, poor applicability to smallholder producers and evidence of ongoing biodiversity destruction by certified plantations.[33,34] **In scaling up BiCRS, it will be important for policy support to include a valid, robust certification system from the beginning, which may need to receive ongoing public funding or other systematic support to ensure its effectiveness**.

Finally, despite the European Union's decision to restrict and eventually phase-out palm oil biodiesel, both Indonesia and Malaysia challenged this decision at the World Trade Organization, with cases still ongoing.[35] This action by these countries is motivated by the large role that palm oil plays in export revenues.[36] This situation highlights the fact that enacting subsidies for producing biomass for climate-related purposes can stimulate the growth of a large cultivation industry by exporting countries, which may later be difficult to slow or stop, a variation of the "eco-colonialism" concern (see Box 3.1). **In scaling up BiCRS, it will be important to consider whether policy support is creating global value chains for biomass production that ultimately overwhelm sustainability considerations in favor of economic ones**.

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CHAPTER 6:

CONVERSION PROCESSES

The term bioenergy denotes the conversion of biomass into energy or energy carriers, including electricity, heat and 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 US (primarily from maize and soy) and Brazil (sugar cane). However, most decarbonization plans now envision wide scale-up of production of liquid transportation fuels and other modern energy products from non-consumable cellulosic biomass feedstocks, also known as lignocellulosic feedstocks.[1] To the extent that energy extraction involves oxidation of part or all of the biomass carbon to CO_2, process modifications are necessary to ensure that bioenergy systems permanently store carbon.

A wide range of technologies for converting biomass to energy, products and services have been developed or proposed. Biomass conversion is generally divided into biochemical or thermochemical pathways. 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, and most of the pioneering commercial-scale cellulosic biofuel production facilities built to date are based on fermentation.[2] In contrast, thermochemical conversion involves controlled heating and decomposition of biomass into liquid, gaseous and solid byproducts and subsequent upgrading of liquid and gaseous intermediates into finished liquid fuels. The optimal conversion technology in any situation depends in part upon the type of feedstock.

While technical and policy barriers have prevented wide-spread production of cellulosic biofuels, fermentation remains a key technology, both in current biofuel production and in production of carbon-negative fuels. For instance, using existing first-generation corn ethanol facilities with CCS, fermentation produces a pure stream of CO_2 available for carbon sequestration or utilization.[3] CCS can similarly be applied to cellulosic biomass fermentation to produce carbon-negative fuels at larger scales and potentially with a reduced environmental footprint.

Ethanol is produced through fermentation of various grains (*e.g.*, corn, sorghum, barley and wheat) and sugar crops (*e.g.*, sugar cane, sugar beets and sweet sorghum) with CO_2 as a byproduct. Fuel ethanol, like alcohol-based beverages, is produced from the fermentation of six-carbon sugars (*e.g.*, glucose) by yeast. During fermentation, glucose decomposes into ethanol and CO_2 through the following chemical reaction:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

In corn ethanol production, each bushel of corn yields approximately 2.7 gallons of ethanol, 17 pounds of dried distiller grains with solubles (DDGS) and 18 pounds of CO_2.[4] Thus, production of 1 gallon of ethanol generates 6.29 pounds of CO_2.[5] Lignin, one of the components of cellulosic biomass, is recalcitrant to processing by microbes or enzymes. As a result, high-lignin feedstocks, such as softwood biomass, are less amenable to biological conversion[6] or require pretreatment.

In contrast, thermochemical conversion involves decomposition of biomass into liquid, gaseous and solid components, and it often upgrades liquid and gaseous intermediates into finished liquid transportation fuels.[7] While thermochemical conversion technologies, including gasification and pyrolysis, have not yet achieved the same degree of commercial deployment as biochemical technologies, they are highly amenable to carbon-negative configurations, and thus are prime candidates for additional targeted research and deployment support. Optimal, modern 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. Pyrolysis involves controlled heating of biomass in an oxygen-limited or oxygen-free environment under low enough temperatures and short enough times that kinetics still control the outcome. 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 (bio-oil prime among them). Slow pyrolysis optimizes production of a solid carbon-rich fraction called biochar.

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 carbon conversion efficiency is key to understanding the life-cycle impacts of biofuels derived from both biochemical and thermochemical pathways. Thermochemical processes also impart additional feedstock flexibility, including the ability to work with high-lignin softwood species or municipal solid waste.[8]

Thermal or biochemical conversion both yield the product of interest, other byproducts and a significant amount of CO_2 from the conversion process itself. The ratio of these three products varies widely, from combustion for electric power, which turns most of the carbon into CO_2 with a small amount of char, to autothermal fast pyrolysis, which turns about half the carbon into CO_2, 20% into char, and the remaining 30% into bio-oil (the product of interest).

Figure 6-1 shows the most common conversion processes, biomass sources and range of products made from them. In each case, carbon storage is achieved alongside production of an energy product. These products vary widely in their envisioned end-uses, including electricity, gaseous fuels or liquid fuels. On an energy basis, liquid fuels are often the most valuable, while electricity is least valuable. Carbon-negative hydrogen, on the other hand, has numerous applications in transportation, electricity production, fuels production and other industrial processes.

Today the overwhelming majority of lignocellulosic biomass is used to create electricity or heat, with an increasing amount used to make methane by anaerobic digestion. In all cases, the conversion process yields CO_2 directly. In fuels production, between 25% and 50% of the incoming carbon in all the processes in Figure 6.1 typically turns into CO_2 at the processing facility, often at high purity (see Chapter 4). The relatively low cost of CO_2 capture from these high-purity streams makes them logical targets for BiCRS processes to capture and permanently store carbon and also makes them promising first markets.

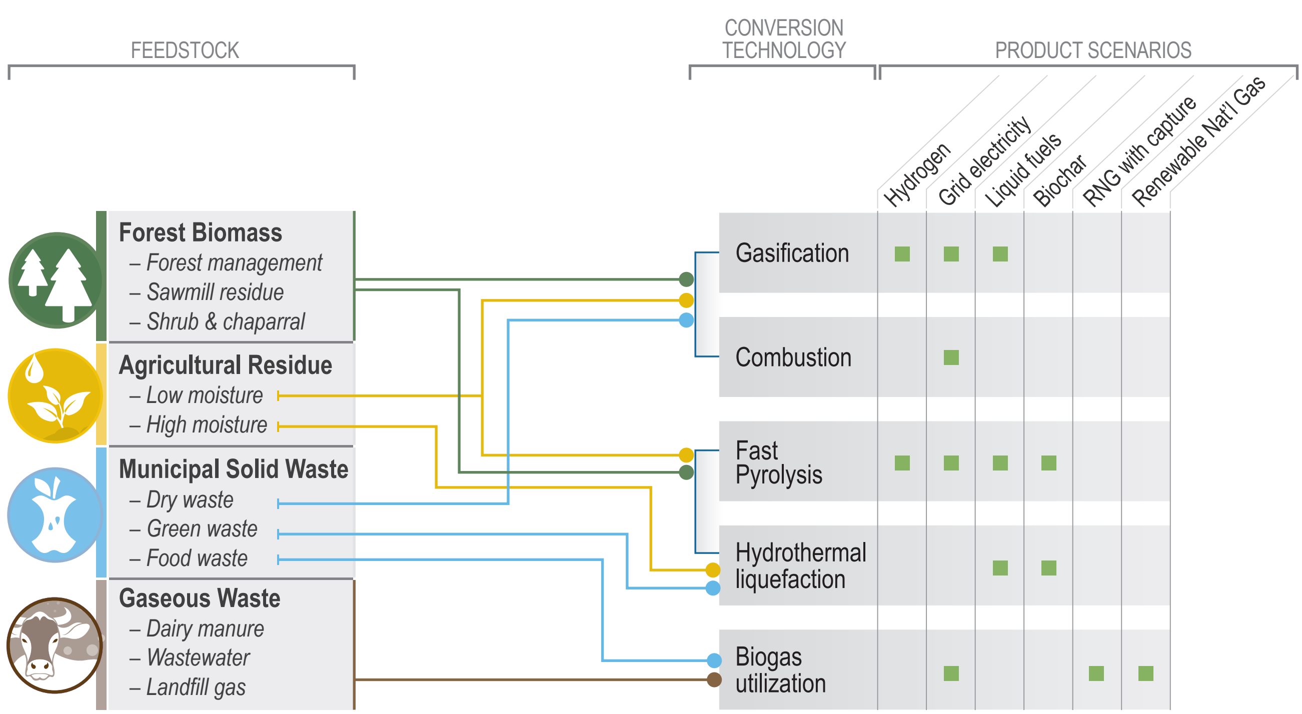

Figure 6.1. *Common biomass feedstocks, conversion technologies and products (Source: Baker et al. 2020, Getting to Neutral[9])*

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CHAPTER 7:

CARBON SEPARATION AND STORAGE

To achieve true net-zero emissions, carbon removed from below the Earth's surface must be balanced by returning carbon below the Earth's surface or storage of that carbon in long-lived products.[1,2] Carbon removed from the Earth's subsurface (the geosphere) through combustion of fossil fuels or other processes must be returned to the geosphere or long-lived products to balance the carbon and climate books.

A number of carbon removal methods rely on storing CO_2 in plants (the biosphere). Although storage of CO_2 in plants can be cheap and produce ecosystem benefits, the duration of such storage is short, the risk of release is high and the potential is limited.

- First, the likely duration of most carbon storage in plants is measured in years or decades, delaying but not preventing climate risks.
- Second, carbon storage in plants can have a high risk of accidental release. (The enormous forest fires in California during 2020 are estimated to have released the equivalent of 90 million tons of CO_2 through mid-September, illustrating the fragility of carbon storage in plants.[3]) Many studies indicate that the risk of accidental release increases with climate change (*e.g.*, Anderegg *et al.*, 2020[4]), in part driven by drought, high temperatures, decreases in soil moisture, fires, biotic agents and other climate-related forcings.
- Third, plants have limited potential to offset anthropogenic carbon emissions. The disequilibria created by these emissions in recent decades are huge, without any historical precedent. Since 75-80% of these releases are outside the domain of land-use and biological system management,[5] biomass-based systems are unlikely to be able to store large enough volumes of atmospheric carbon in relevant time frames.

The technologies and tools of carbon management geological CO_2 storage are well known and understood.[6-8] The total capacity of the Earth's crust to store CO_2 is effectively limitless.[8-10] Conventional geological storage systems like saline formations have an estimated storage volume of 10-20 trillion tons—far more than either annual emissions or total historic emissions. Harnessing this capacity in tandem with biomass conversion makes BiCRS a unique and important approach to deep decarbonization by 2050, helping balance any residual emissions in hard-to-abate sectors. This chapter examines how, in the context of BiCRS, CO_2 can be stored underground or in long-lived products.

Dedicated CO_2 Storage Geography

One of the most promising aspects of BiCRS is the potential for co-location of large biomass supplies and geological storage resources, particularly where they naturally occur in close proximity to each other. Producers and operators have an option to convert BiCRS feedstocks locally, allowing them to store CO_2 locally and ship decarbonized products as described in Chapter 5. This option creates several benefits, including local jobs, greater local economic and tax benefits, and lower mass for shipping (most obvious if producing hydrogen locally). Because of the prohibitive cost of long-distance CO_2 shipping, this approach requires local CO_2 storage capacity (Figure 7.1).

Several important geographies have both high biomass potential and high CO_2 storage potential.

- Southeast and Central US: The softwood timber forests of the southern states are well known for pulp and paper production and for supplying wood pellets. The corn-belt of the Midwest is well known for producing grain, corn and ethanol. The extraordinary geological storage potential of these areas is less well known. Yet the Gulf of Mexico and Illinois Basin together provide a storage capacity of close to 1 trillion tons of CO_2.[12] Already, the world's first BECCS project in Decatur, Illinois shows the promise of BiCRS in the region. The region also hosts one of the world's most impressive shipping and logistics infrastructures, including Mississippi river barge traffic and the industrial ports of Houston, Port Arthur, New Orleans and Mobile.
- Southeast Asia: The forests of southeast Asia host some of the world's largest palm-oil plantations, hardwood timber supplies, bamboo forests and rice plantations. Very large and productive sedimentary basins underlie these regions, including Sumatra, Borneo and Malaysia. Southeast Asia also straddles the world's most trafficked marine transport systems

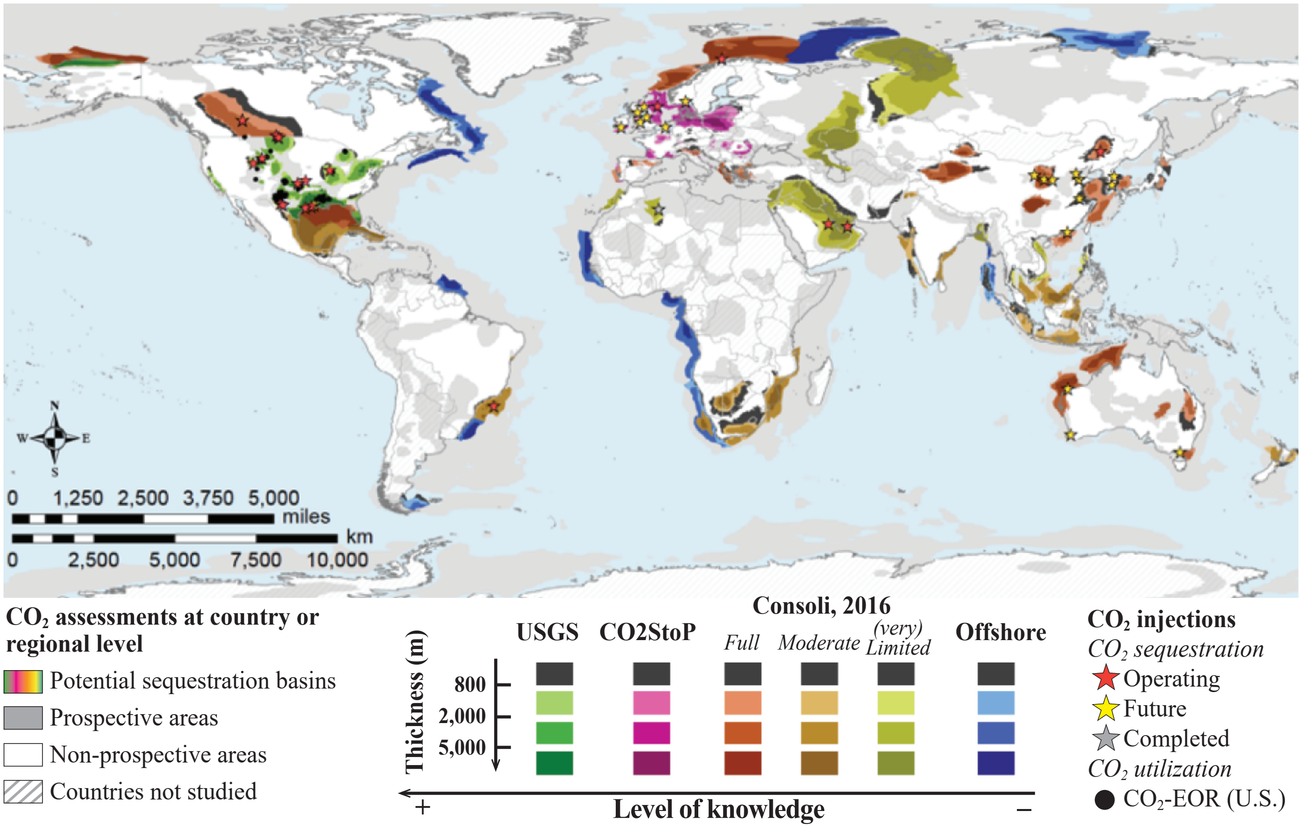

Figure 7.1. *Distribution of conventional CO_2 storage worldwide. NOTE: Some areas are not fully explored and characterized. Source: Kolosz and Wilcox, 2020*[11]

through the Molucca straights, run from enormous logistics hubs and terminals including Singapore, Shenzhen and Hong Kong.

- North Sea: Much of the world's bioenergy is consumed in the North Sea region, including the Drax plant at Humber and biodiesel consumption in northern Europe. Biomass products enter the large industrial ports of the region and are often converted or upgraded on site. These ports border well mapped and understood CO_2 storage resources under the North Sea, including Scotland, the Netherlands and coastal Norway. This region hosts the world's first commercial-scale CO_2 storage project (Sleipner) and the world's first CO_2 shipping project (Northern Lights).
- California and Alberta: These two geographies combine excellent geological storage options, world-class farming and agribusiness. They also lie adjacent to enormous timber stands and working forests. Importantly, insect infestations have killed hundreds of millions of trees in these areas, creating both a terrible fire risk and potential BiCRS feedstocks.[13] Alberta boasts some of the best CO_2 storage infrastructure in the world, including the new Alberta Carbon Trunk Line and three projects storing CO_2 from hydrogen production (none yet from biohydrogen). California is under active development for CO_2 storage and appears to be able to store tens of billions of tons of CO_2 with BiCRS.[14]

BiCRS-Specific CO_2 Capture

Biomass conversion produces by-product CO_2. Although some conversion approaches (such as combustion for power generation) are well-suited to conventional CO_2 capture, other approaches (such as production of liquids by fast pyrolysis) are not. Several conversion approaches present opportunities (such as low-cost capture from high-purity sources) that could be relevant as BiCRS scales.

Gasification: Biomass gasification has produced power and chemical feedstocks for years, notably in Europe. Many studies see opportunity for scaling up gasification of biomass (especially woody or cellulosic feedstocks) and conversion to hydrogen or carbonaceous fuels. In these systems, CO_2 can be fully or partially separated using conventional liquid solvents and water-gas shift reactions. However, many cellulosic feedstocks create a challenge for ash-handling systems, including rapid consumption of refractory linings, agglomeration and plugging.[15] Additional work should focus on modified gasifier designs specifically built for biomass (*e.g.*, for biomass-produced ash and better heat balance for heterogeneous feedstocks).

Fast pyrolysis: Pyrolysis involves heating biomass in a low-oxygen environment. Products are a mixture of gas, liquid and solid. In slow pyrolysis, low temperatures are used to remove water and some organic vapors, leaving biochar—a charcoal-like residue—as the principal product. In fast pyrolysis, somewhat higher temperatures are used to break down organic components into a mixture of oils and sugars that can be utilized for liquid fuels. These systems still produce some biochar (typically ~10 % of the original mass). Fast pyrolysis systems can be relatively small compared to gasifiers and are generally considered to be useful in distributed systems where biomass is transported a short distance and the valuable bio oils, sugars and biochar are then transported to where they will be used. Variations in the temperatures, processing times and capture of volatile products create a large number of options in pyrolysis systems.[16]

Fermentation: Conventional fermentation merits special consideration due to by-product release of high-purity CO_2. This stream can be captured, compressed and stored with very low additional costs.[17] This is the basis for the Archer Danials Midland Company (ADM) project in Decatur, IL and is also the largest source of CO_2 for the US merchant market.[18] This feature of fermentation creates potential opportunities in key geographies (*e.g.*, cane ethanol in Brazil), as well as potential future opportunities for cellulosic ethanol production. Economic analysis of potential ethanol developments should include capture and storage of this pure by-product CO_2 and seek CO_2 removal opportunities accordingly.

Biogas and anaerobic digesters: Landfill and digester biogas commonly contain large fractions of both methane and CO_2. Many conventional technologies exist to separate these two gases. Unfortunately, most of these technologies are developed to operate at high pressure. Since biogas is produced at ambient pressures, separation of CO_2 commonly requires substantial cost increases, either through pressurization or oxy-fired combustion. Thus, low-temperature biogas separation technology would assist in capturing the co-produced CO_2.

Storing CO_2 in Long-Lived Products

CO_2 can be stored in a number of long-lived products.[19,20] The idea of a "circular carbon economy" has recently gained prominence and attention (*e.g.*, Circular Carbon Network, 2020[21]; IEF 2020[22]).

Concrete & durable carbon

Concrete, composed of cement and aggregate (sand and gravel), is the second most used substance on Earth after water, with tens of billion tons of annual production and use. Concrete is very long-lived, commonly lasting for over 100 years and in many cases for thousands of years. The large volume and durability of concrete makes it an attractive target for CO_2 storage. Novel formulations of cement allow CO_2 to cure and bind concrete while effectively trapping it in mineral form. In addition, CO_2 can be converted to minerals and used as aggregate and similar additives. If the CO_2 entering this system comes from biomass conversion, this CO_2 has been removed from the atmosphere and would be stored for the long-term.[23]

One can also add biomass fibers to cement and concrete.[24,25] Although this approach provides some benefits in terms of material performance, it is unclear how well it will scale. CO_2 can also be converted to other durable carbon forms, such as carbon nanotubes, carbon black and carbon composites. Current markets for these products are small[26] but have the potential to displace certain building materials (*e.g.*, steel rebar) and scale. As in the case of concrete, if the CO_2 used is biomass-derived, that CO_2 has been removed from the atmosphere and stored for the long-term.[23]

Biochar

Biochar is a recalcitrant charcoal created from pyrolysis of biomass at high temperatures (300-700 °C).[27] Biochar can be used in many capacities. In the agriculture sector, its most prominent uses have been as an animal feed and as a soil amendment. When biochar is added to agricultural soils, it can increase crop yield by enhancing soil hydrological and nutrient properties.[28] However, numerous applications for biochar are emerging outside of the agricultural sector. For instance, biochar has potential applications in the transportation (concrete filler), water treatment (filtration), building (filtration,

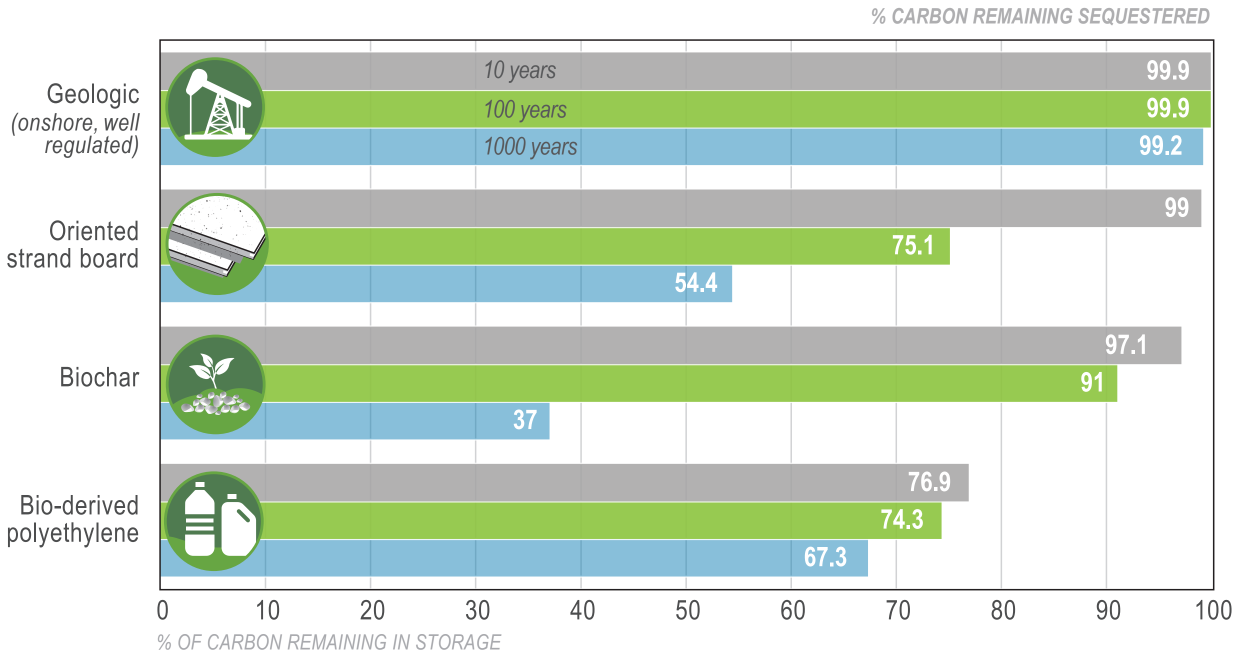

Figure 7.2. *Multiple products can contribute to CO_2 removal over geologically relevant time periods. Estimates of carbon remaining sequestered over 1000 years. Source: Dees et al.*[30]

BOX 7-1 Direct bioliquid injection and disposal (DBID)

Deep disposal of CO_2 lies at the center of most prior research, regulation and policy analysis associated with bioenergy production (BECCS). However, deep geological disposal of CO_2 is not the only potential pathway for BiCRS carbon removal. It is possible to convert biomass into a form well suited for disposal and directly store this biomass in deep geological formations. For example, gasification or fast pyrolysis can convert biomass to bioliquids or bio-oils which can then be directly injected underground without further processing. One clear benefit to this approach is avoided costs for downstream conversion—if the goal is CO_2 removal and geospheric return, then this approach avoids the downstream capital and operating costs associated with further conversion.

One company, Charm Industrial, is developing this technology. Charm currently gathers bio-oils from a fast pyrolysis unit in Canada, ships the liquids to Kansas and injects them into fit-for-purpose salt caverns for disposal. The company plans to improve this system through co-location and process intensification.

This approach has several clear benefits. First, bioliquid disposal in the US requires a Class IA permit for injection (non-hazardous well), which is a lower regulatory burden than that for CO_2 disposal with a Class VI well. Use of existing Class II wells (oil-field injection) is also possible and could further reduce cost and regulatory burden. The second benefit is cost savings (see above). This approach also has substantial limitations. One is that the only salable product is CO_2 removal services, so no other revenues are available to cover upstream conversion costs and processing. Second, there is no policy support today to provide revenues for this approach—neither 45Q nor the CA low-carbon fuel standard recognize bio-oil disposal as qualifying. It is unclear if this approach qualifies under the European Trading System.

insulation), electronics, cosmetics, textiles and medical sectors.

Although still in its nascent stages, a market for biochar in the US is steadily growing. The US Biochar Initiative (USBI) estimated that 200,000 bone dry tons of biomass are consumed yearly to create biochar and that 35,000-70,000 tons per year of biochar are currently produced in the US.[29] Currently, markets for biochar are not well established as there is substantial volatility and uncertainty surrounding biochar prices.[31] Additionally, while farmers are considered the primary customers of biochar, wide adoption of biochar into agricultural practices has not yet been achieved. Industry participants are now focusing on educating farmers to help scale the industry.

Wood & durable bioproducts

There is an extensive literature on the emissions and sequestration benefits of storing carbon in long-lived wood products, particularly in buildings. One prominent example is oriented strand board (OSB), an engineered wood panel widely-used as a load-bearing construction material. Like polyethylene, OSB undergoes a multi-phase life, with a use-phase and an end-of-life phase that may involve recycling or secondary use and a significant portion managed in landfills.

There are additional emerging innovative wood products, including mass timber. Mass timber is a commercially fabricated composite panel product composed of cross-layered pieces of dimensional lumber or wood veneer bound together by structural adhesives, nails or dowels, so that the whole panel acts as a single load-bearing or floor element. Mass timber products are all relatively new to the US but well developed in Europe and Japan. These products enable use of wood for buildings taller than the current limit of 65 feet, enabling greater use of timber in construction. They allow weight reduction in buildings, thus reducing seismic demand on the building's lateral system and reducing gravity system foundation loading. Challenges include market formation activities, testing of commercial tree species of particular interest, and utilization of non-merchantable biomass.[32]

Long-term sequestration of biogenic carbon can also be achieved in plastics, such as polyethylene (PE). Plastics are engineered to resist physical and biological degradation. At the end of the use-life of a PE product, it may be recycled, re-used, combusted, landfilled or discarded. In the US context, most PE will be landfilled, where only a fraction of the degradable carbon will return to the atmosphere. The lifetime of plastics in the environment is not well-understood and estimates vary widely.

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CHAPTER 8:

RESEARCH AGENDA

For BiCRS to achieve its full potential, research on a wide range of topics is essential. Technology and social science issues are both important. This chapter discusses research needs in the years ahead.

A. Technology

1. Hydrogen

Biomass can be used to produce hydrogen, with CO_2 emissions from these processes captured and stored. Most existing literature focuses on biomass gasification, followed by water-gas-shift and CO_2 removal, to produce hydrogen at large scales. Research needs for this approach include the following:

- Biomass feedstock handling and pre-treatment methods, as well as autothermal processes that require no external fuel
- Integration of hydrogen production with transportation, such as liquefaction or conversion to ammonia

In addition, two less-studied conversion processes may be useful:

- *Pyrolysis-based methods*, including the use of catalytic steam reforming to produce hydrogen from bio-oil. Pyrolysis processes are typically smaller scale than gasification processes.
- *Supercritical water extraction*, which involves the use of supercritical fluid solvent. Supercritical water gasification can deal directly with wet biomass without drying and has high gasification efficiency at lower temperatures than air or steam gasification.

2. New pathways not linked to energy production

Many BiCRS processes that produce energy are relatively advanced and well understood. In comparison, many pathways that do not produce energy are under-explored. These pathways present enormous opportunities for CO_2 removal that merit attention from the research community:

- *Biochar*: While biochar potentially represents a stable, long-term form of carbon storage in soil, physical characteristics of the feedstock and processing steps, as well as environmental factors such as precipitation and soil conditions, strongly influence this stability. As a result, there is a large degree of uncertainty in the durability of carbon sequestration in biochar. In addition to engineering and better modeling of carbon stability, supportive market research and market development is necessary to increase demand for biochar.
- *Engineered wood products:* Various forms of lumber can be treated to produce durable construction materials, including cross-laminated timber and wood-fiber insulation boards. These products can substitute for conventional construction materials, such as concrete and steel in some architectural applications, displacing associated emissions and storing carbon in a durable form.[1] Research is needed on improved methods of treatment, advanced construction techniques and new application areas.
- *Bioliquid injection:* As mentioned in Chapter 7, the private sector is beginning to pursue deep geological disposal of bioliquids as an alternative form of geospheric return. With the goal of bioliquid disposal, many additional potential conversion approaches can be considered (*e.g.*, direct liquefaction and maximizing production of black liquor). Processes that avoided production of bioliquids as waste can instead be optimized with deep disposal in mind.
- *Macroalgae abyssal dispatch:* As a biotic means of CO_2 drawdown, macroalgae has specific benefits, including lack of land and fresh water requirements and direct removal of CO_2 from oceans (thereby reducing local acidification) as mentioned in Chapter 4. Bypassing harvesting and conversion, one can instead send kelp and seaweed intact to the deep ocean, avoiding the costs of drying and processing and maximizing CO_2 removal. Several research groups (*e.g.*, Yale Carbon Containment Lab[2]) and companies (*e.g.*, Running Tide[3]) have begun work on macroalgae disposal schemes, including cultivation of negatively buoyant kelp (which would require no processing to dispatch to the abyssal plain).
- *Biofiber entombment:* Biofibers have been considered optional additions to cement and concrete as means of enhancing their performance, either for strength or durability.[4] Addition of microfibers can reduce the

total required amount of cement in concrete mixes for construction, with both economic and environmental benefits. Although still at an early stage, these composite materials could potentially store large volumes of carbon as biofiber composites. Research to better understand preferred feedstocks, treatment requirements, techno-economics, performance and total potential loadings are needed.

This list is by no means exhaustive. Rather, it is meant to illustrate the opportunities in a BiCRS framework.

3. Modular fast pyrolysis

We believe that further development of modular systems could contribute to meaningful BiCRS, including its criteria for carbon removal and do-no-harm. As discussed above, pyrolysis processes are typically smaller scale than gasification processes and may be more suitable for dispersed biomass resources. Two challenges persist. The first is the complex chemistry of produced pyrolysis products, which can lead to clogging and deposition of tars and other residues in the capture equipment. Upgrading and processing bioliquids to usable products presents consistent challenges, though commercial developers like Ensyn have made significant progress. Development of methods to make bio-oil stable over longer times and more easily refined into transportation fuels will be important for large-scale application. Also, many fast pyrolysis units are relatively small and modular, producing biochar as its primary form of carbon removal. Some CO_2 is commonly produced during fast pyrolysis, either in association with syngas and bioliquids or from application of external heat. CO_2 capture and storage would require low-cost modular capture technology to match their output. Overcoming these challenges should be the focus of applied R&D to improve the performance, capacity and modular construction of fast-pyrolysis units.

4. Satellite monitoring and data analysis

Because of the importance of land use/land cover (LULC) change to the life-cycle emissions associated with BiCRS, any large-scale implementation will require careful monitoring of LULC in all locations that provide biomass. LULC change can be monitored in a variety of ways, but the most effective approach is to use satellite-based remote sensing, which allows global coverage and relatively high precision. Many governments operate Earth-observing satellites for this purpose and make the resulting data freely available online shortly after it is acquired. In general, this makes it possible to track changes to the amount and type of vegetation on land surfaces in near-real time, within days of the changes occurring, as well as to make forecasts of future productivity.[5,6]

Earth-observing satellites use two basic sensing methods to measure the type and amount of vegetation on land surfaces: optical and radar.[7-9]

Optical sensors, such as the Operational Land Imager (OLI) on the US Landsat 8 satellite and the MultiSpectral Instrument (MSI) on the European Space Agency's Sentinel-2 satellite, passively measure reflected sunlight from the Earth's surface in optical and near-infrared wavelengths.

- Earth-observing satellites with optical sensors capture imagery from almost all land locations on Earth (extreme north and south latitudes are usually excluded) and revisit each location in intervals ranging from days to weeks. To minimize variations in solar illumination between returns, these satellites are commonly placed in sun-synchronous orbits, meaning that they revisit locations at the same time of day (during daylight hours).
- Despite the many advantages of this sensing method, it suffers from the inability to image through clouds. This is a significant limitation, particularly in tropical and subtropical regions that have high cloud cover. In some cases over half of revisits fail to produce usual imagery because of cloud cover, slowing the rate at which LULC changes can be detected.[10]

Radar sensors, such as the Phased-Array L-band Synthetic Aperture Radar 2 (PALSAR-2) instrument on the Japanese ALOS-2 satellite and the C-Band Synthetic Aperture Radar (C-SAR) instrument on the European Space Agency's Sentinel-1 satellite, actively scan L-, C-, or X-band microwave energy toward the Earth's surface and measure the amplitude and phase of the reflection.[11, 12]

- These instruments can measure details of the surface elevation at transverse resolutions of several meters and sub-meter vertical resolution. These measurements can be analyzed to yield detailed information on the canopy height of forested areas and the vegetation type and quantity in other areas.

- Importantly, the microwave frequencies used by these instruments penetrate through clouds, meaning the sensors are able to produce useful data even in regions with extensive cloud coverage. Further, because the sensor does not require reflected sunlight, it can take measurements at night, increasing the effective revisit rate.

Optical and radar spaceborne measurements can be supplemented by LiDAR measurements. While LiDAR operates on a similar principle to radar, it uses optical wavelengths and is therefore able to resolve much smaller details, giving it higher spatial resolution. In the context of biomass measurements, this type of sensing is able to penetrate through the forest canopy to measure forest structure in three dimensions, which can be extremely valuable in improving biomass quantification.[13-15] LiDAR is primarily used on airborne platforms, meaning that data are only acquired infrequently and are limited in spatial extent. However, it has begun to be used from orbit for forest monitoring, notably the Global Ecosystem Dynamics Investigation (GEDI) system on board the International Space Station[16] and the Ice, Cloud and Land Elevation Satellite-2 (ICESat-2).

The breadth of remote sensing data available for LULC monitoring has led to the growth of a large international academic research community on the topic. However, the results of this research are often difficult to translate into policy contexts since they involve complex analyses and are not designed for continual operation. To serve this need, projects have emerged to rapidly translate the remote monitoring results into more accessible formats for policymaking, enforcement and related uses. These projects include Global Forest Watch, CropWatch, the Forest Observation System, Global Fishing Watch and Climate TRACE, among many others.[17]

Many needs remain for enhancing LULC-monitoring capability and ensuring it continues to be available into the future:[18]

- **Governments must continue to invest in development, launch and operation of Earth-observing satellites.** While the increasing availability of private, commercial satellite imagery can be helpful for biomass monitoring, it cannot substitute for flagship remote-sensing missions by the public sector.
- **Governments should commit to the maximum reasonable degree of Earth observation data availability,** including use of modern data-indexing and-retrieval systems for optimal data access.
- **Development of algorithms for interpreting raw remote sensing data and refining biomass estimates is a priority,** particularly with the introduction and application of advanced machine learning methods.[19] Governments should support continued R&D in this area.
- **Governments and private purchasers of biomass for carbon removal should proactively develop systems for LULC monitoring,** either individually or in partnerships, and commit to using those systems to track the impacts of biomass purchases. Additionally, purchasers should develop clear guidelines on what land-use practices are acceptable and suspend purchases if these practices are not followed.

5. Plant breeding and genetic modification to enhance carbon uptake

While significant research attention has been paid to developing optimal crops for energy production, far less research has focused on developing crops that optimize life-cycle carbon removal. Such a "carbon-optimized" plant could be part of a BiCRS system that achieves far higher carbon removal rates than a system using wastes or even conventional dedicated energy crops.

Research to develop this kind of plant using plant breeding or genetic modification would focus on several factors in the plant life-cycle. One of these is to identify and breed varietals that increase soil carbon during growth, using *in situ* measurement tools and other methods such as those under development by the US Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) ROOTS program.[20] A related approach is to identify varietals that are optimized for a particular biomass conversion mechanism, which may include improved susceptibility to thermochemical treatment or pelletization. A complementary approach would be to focus on engineered enhancements to the efficiency of photosynthesis in fixing atmospheric carbon, including improvements to the enzyme Rubisco to speed up turnover time and reduce oxygen fixation leading to photorespiration[21]; optimization of other enzymes in the Calvin-Benson cycle[22]; and increasing photoprotection recovery.[23]

An additional approach is to modify the durability of plant biomass. Increasing the durability of biomass (recalcitrance) could delay decomposition and the release of stored carbon through techniques such as enhanced expression of the biopolymer suberin[24] and enhanced metal hyperaccumulation for fungal resistance.[25] This approach would be preferable for BiCRS approaches that result in durable biomass products with minimal conversion. An alternative strategy is to decrease the durability of biomass by methods such as downregulating the production of lignin or enhancing the incorporation of molecules in lignin that aid biomass pretreatments.[26] This strategy would be preferable for conversion-intensive BiCRS approaches in order to reduce the cost and energy consumption of conversion.

In addition to these individual engineering techniques, a comprehensive R&D effort of the potential for plant breeding or genetic modification to contribute to BiCRS would include a system-level "carbon impact" assessment of the plant and the full life-cycle of harvest, treatment and use. The holistic impact on plant carbon fixation rates from these pathways remains poorly understood, as does the potential impact on soil carbon accumulation.[27]

B. Social Science

Very large-scale deployment of BiCRS could affect food security, clean energy development, biodiversity, water resources and other services of value to society. (See Gough and Vaughan, 2015[28]; Fuss *et al.*, 2014[29]; Smith *et al.*, 2016[30] for discussion of these issues related to BECCS). Addressing the relationship between these topics and BiCRS will require social science research drawing from a number of disciplines including economics, political science and sociology, as well as related fields including agronomy, nutrition, hydrology and engineering.

Economics provides essential tools for understanding indirect land-use change, for example. When examining the impact of agricultural and energy policies in one market with land-use change far away, prices and capital flows provide important information. Political science provides important tools for evaluating policy options for promoting BiCRS and designing multinational institutions to help track biomass trade and other topics. Sociology provides important tools for understanding community dynamics in response to the growth of BiCRS.

In the study of carbon removal using biomass, technologies often get more attention than social science questions, such as who provides the biomass, how is that controlled and who benefits?[31, 32] In addition, the existing social science research related to BiCRS often focuses on "barriers" to technology adoption, rather than exploring technology adoption as an inherently social process. The limited research relevant to BiCRS looks at public acceptance or social license, rather than opportunities for communities. Future research can move beyond "social impact" to identify opportunities for communities along the BiCRS value chain.[33]

Policy research will also be central to the development of BiCRS. We discuss policy issues in Chapter 9.

Interdisciplinary social science research can help illuminate the social dynamics of BiCRS more broadly. One leading author divides this social science research into four categories[33]:

1. Synthesis research that looks at recent and current lessons on carbon-sink enhancement, scaling up biofuels/the bioeconomy, and past and present energy transitions, including on the investment gap with CCS and clean energy technologies
2. Regional and landscape-level analysis of carbon-removal technologies
3. Analysis of policymaker and citizen demand for and knowledge of negative emissions
4. Work on technology diffusion, adoption and transfer into different socio-economic contexts

Each of these kinds of studies advance BiCRS by increasing social demand.

The authors of this document are not social scientists but believe social science issues are of central importance with respect to BiCRS. This is an important area for future work, which we have only had the opportunity to partially develop in this roadmap.

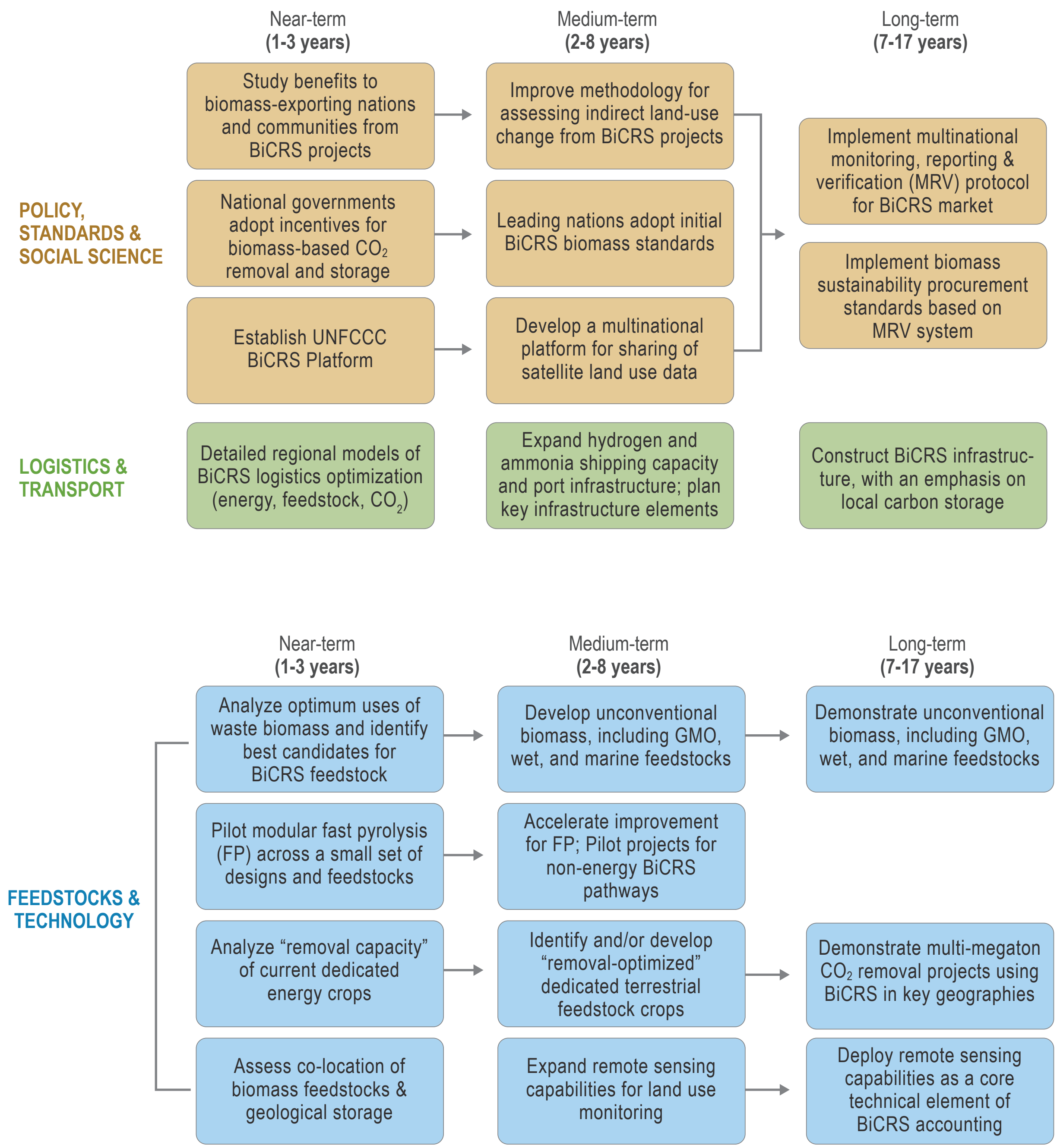

Figure 8.1. *Innovation Roadmap – Biomass Carbon Removal and Storage (BiCRS)*

C. Integrated Analyses

In addition to research on discrete technology and social science issues, integrated analyses addressing both technology and social science issues will be required for BiCRS to scale. Techno-economic assessment, which addresses both technology and economic issues, is one of the most familiar forms of this type of analysis.

Life-cycle greenhouse emissions analyses will be especially important as BiCRS scales. BiCRS processes can be complex, involving a wide range of inputs, transport across considerable distances and second-order impacts. Understanding the emissions implications of all parts of a BiCRS process is essential to evaluating whether that process has achieved its principal goal: net removal of carbon from the atmosphere. These lifecycle analyses may often require insights concerning both technology and social science issues.

D. Research Timeline

Significant resources will be required for the research agenda described above. For BiCRS to scale, some topics must be addressed in the near-term while other topics can be evaluated over longer time periods. We suggest the following rough timeline for BiCRS research priorities.

Near-Term (1-3 years)

- Identify waste biomass volumes around the world and alternative uses for it
- Evaluate jobs potential associated with BiCRS implementation
- Evaluate local opportunities based on biomass availability, technology choice and product need
- Evaluate relative merits of biomass transport versus local processing and storage versus CO_2 transport to new locations
- Evaluate markets for solid products like engineered wood and wallboard
- Conduct intensive applied R&D program on improving the performance, capacity and modular construction of fast pyrolysis units
- Determine and reduce environmental impacts of BiCRS facilities
- Develop clear rules for evaluating the environmental, climate, economic and social impacts of BiCRS
- Analyze new and existing data on the impacts, benefits and tradeoffs of dedicated biomass from forests

Mid-Term (2-8 years)

- Evaluate if ongoing or new use of standing timber should be included as an appropriate biomass resource, based on new data and analyses
- Evaluate ability to supplement waste biomass with environmentally harvested annual crops
- Evaluate ability to grow and harvest longer-rotation crops like poplar
- Determine the likely impact of production of these crops on worldwide agricultural supply
- Determine the local jobs impact of dedicated BiCRS crops
- Determine the environmental impact of these crops
- Create a framework for determining the overall risk/benefit balance of growing and using these crops locally; extend framework to the benefit of exporting these crops and receiving significant climate service payments from receiving countries
- Develop both local and remote means to monitor and ensure that environmental and climate goals are being met by local implementation of BiCRS
- Evaluate the social impact of early adoptions of BiCRS

Long-Term (7-15 years)

- Evaluate the global capacity for BiCRS under social, economic and environmental constraints
- Develop high-efficiency BiCRS facilities, especially for products determined to be most beneficial locally
- Evaluate whether first-of-a-kind BiCRS technologies still meet social, economic and environmental goals or whether they should be phased out

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CHAPTER 9:

POLICY

Policy tools are essential for BiCRS to play a meaningful role in climate change mitigation. These policies fall into three broad categories:

- First, incentives for removing carbon from the atmosphere
- Second, support for development and deployment of BiCRS technologies
- Third, standards for BiCRS projects, including for measuring life-cycle carbon emissions impacts

This chapter discusses policies that could help BiCRS become an important contributor to net-zero emission. Some of these policies are not just helpful but essential to any significant scale-up of BiCRS.

A. Incentives for Removing Carbon from the Atmosphere

Governments play a central role in providing incentives for carbon removal. Without governments providing such incentives, few businesses would invest in BiCRS or other carbon removal projects. While some large businesses have made initial investments in carbon removal technologies as part of their voluntary sustainability programs, this is limited in scale.

There are small markets for CO_2 removed from the atmosphere, most notably for enhanced oil recovery (EOR)—indeed three U.S. ethanol plants currently supply CO_2 for EOR. There are also small markets for voluntary CO_2 offsets. Neither EOR nor voluntary offsets provide sufficient demand for BiCRS to scale, and thus government policies are essential.

Available tools include emissions trading programs, tax mechanisms and mandates.

1. Emissions trading programs

Under emissions trading programs, the right to emit requires a permit. Governments give or sell these permits to emitters, who may then trade the permits among themselves. Under many emissions trading programs, governments gradually reduce the number of permits (often called emissions allowances), thereby reducing total pollution.

An emissions trading program can easily be designed to provide incentives for carbon removal. The most straightforward way is to authorize facilities that remove carbon from the atmosphere to sell allowances equal to their removals. That approach provides BiCRS and other carbon removal facilities with a financial reward for sequestering carbon. (These removals need to be measured on a full life-cycle basis—a challenging issue discussed below.)

Emissions trading programs for CO_2 are now in place in the EU, California, the northeast US, Canada and seven Chinese provinces, among other places. The Chinese government is in the process of launching a nationwide emissions trading program for the power sector. However, we are not aware of any emissions trading program that provides credits for carbon removal.[1]

2. Tax mechanisms

Tax policy can provide incentives for BiCRS and other carbon removal processes. A carbon tax provides incentives to reduce emissions to zero, although not below zero. However, governments can also provide tax incentives for carbon removal, such as a tax credit for each ton of CO_2 removed from the atmosphere and then sequestered.

The Section 45Q Carbon Capture Tax Credit in the US provides a tax credit for each ton of CO_2 sequestered, although there is no requirement that the CO_2 be removed from the atmosphere first. (The CO_2 can come from fossil fuel combustion or other sources.) Nevertheless, Section 45Q has already helped launch

BiCRS projects associated with ethanol by-product CO_2 and saline formation storage in the US. Enacted in 2018, Section 45Q provides tax credits of $50 per ton for CO_2 sequestered in geologic formations and $35 per ton for CO_2 used in products such fuels or cement. To achieve wider uptake, the statute would require increased valuation. For carbon removal in a form other than CO_2 (*e.g.*, bioliquid injection), amendment of 45Q or new statutes would be required.

Carbon prices are in use in many jurisdictions around the world, including Norway, Sweden, Switzerland, New Zealand and British Columbia.

3. Mandates

Perhaps the simplest way for governments to provide incentives for BiCRS is to require it. For example, government mandates could require bioenergy facilities to sequester a certain percentage of the CO_2 released in their processes underground or in long-lived products. Current mandates (*e.g.*, military procurement of biofuels or the US Renewable Fuel Standard) could require additional CO_2 removal through CCS or another BiCRS pathway.

Government mandates can be effective in helping reduce emissions and build markets for clean energy products. In the US, many state governments require utilities to purchase a minimum percentage of their power from renewable sources. In India, a similar requirement is imposed by the Ministry of New and Renewable Energy. These requirements have been important to the early growth of wind and solar power in both countries.[2]

Other experiences with government mandates suggest caution, however. The US federal government has required the use of cellulosic ethanol in fuel supplies for more than a decade. Nevertheless, the cellulosic ethanol industry remains in its infancy. Waivers to this requirement have been granted on a regular basis. Technology-forcing requirements—in which governments require private actors to meet standards that are not yet technically achievable—have been successful in some instances but not in others.[3]

B. Support for Research, Development and Deployment

1. Research and development

National governments spend roughly $15 billion annually on R&D for clean energy technologies. These programs have played important roles in the development of countless technologies in recent decades.[4]

Several recent government R&D programs have targeted biomass carbon removal and storage technologies. Europe has launched three major negative emissions projects that include biomass as part of Horizon 2020: NEGEM[5], led by VTT, looking at biomass-based negative emissions; LANDMARC, led by Tu Delft, focusing on remote sensing; and OceanNETS led by Geomar Helmholtz Center, focusing on oceans. US efforts include ECOSynBio (Energy and Carbon Optimized Synthesis for the Bioeconomy), a program of the Advanced Research Projects Agency-Energy (ARPA-E) at the US Department of Energy, which will pioneer a new paradigm for biosynthesis that prioritizes carbon and natural resource efficiency during the production of renewable carbon-based fuels, chemicals and products. The International Energy Agency (IEA) has supported research on BiCRS value chains, regional opportunities and technology roadmapping.

In December 2015, heads of state from more than 20 countries announced Mission Innovation, a coalition dedicated to accelerating clean energy innovation. Member governments (including Japan, China, the UK, Germany and Saudi Arabia) pledged to double R&D on clean energy within five years. The increase in R&D budgets from these countries in the years ahead offers an opportunity to increase government R&D funding for BiCRS.

The US helped launch Mission Innovation and remains a member. Although the US will not fulfill its overall doubling pledge under the Trump administration, the US Congress has increased clean energy innovation budgets by 25% in the past four years, notwithstanding Trump administration proposals to cut those budgets.[6]

2. Deployment

BiCRS facilities are large and capital intensive. First-of-a-kind BiCRS facilities are unlikely to be able to attract private capital in amounts sufficient for initial deployment. (This is the classic second "valley of death" for energy technologies.) Governments play a central role in supporting deployment of such projects.

Government support for deployment can take several forms, including the following:

a. **Tax Incentives.** Tax incentives can play an important role in spurring deployment of clean energy technologies. In Norway, for example, generous tax incentives helped plug-in electric vehicles capture 50% of new car sales in 2018.[7] In the US, federal tax incentives have played an important role in promoting deployment of solar and wind power.

   Tax policy can incentivize BiCRS with credits for each ton of CO_2 removed and stored, as noted above. In addition, tax policy can incentivize deployment of the technologies required for BiCRS to scale. There are many possible structures for such tax incentives. They include the following:

   i. **Investment tax credits**. Governments could provide businesses a tax credit for a percentage of the capital costs incurred in deploying BiCRS. (This would be similar to the US federal government's investment tax credit for solar power, which has historically provided a tax credit of 30% of the cost of any solar installation in the US.)

   ii. **Production tax credits.** Governments could provide a tax credit for each ton of carbon removed from the atmosphere and stored by a BiCRS facility. (This would be somewhat similar to the US federal government's production credit for wind power, which provides a tax credit based on the kWh of wind power sold at a facility.) Because some companies do not have tax liabilities, governments can provide refundable tax credits or cash payments in lieu of tax credits under these programs. (Section 1603 of the American Recovery and Reinvestment Act was an example of such a program.[8])

   iii. **Waiver of sales, value-added taxes or import taxes**. Governments could waive taxes that would otherwise be imposed on any products manufactured at BiCRS facilities. (This would be similar to Norway's incentives for electric vehicles, which include waivers of the import and sales taxes that apply to conventional vehicles.)

b. **Grants.** Grants are among the most direct ways to provide financial support for the low-carbon transition. Grant programs are widespread in many countries, often to assist in deployment of first-of-a-kind or early-stage technologies. Governments could provide grants to help defray the capital costs associated with building BiCRS facilities.

c. **Loan Guarantees.** Cutting the cost of debt capital can help make a project financially viable. Government loan-guarantee programs seek to cut costs of debt financing by reducing risk to lenders, resulting in lower borrowing costs. The US Department of Energy's loan-guarantee programs helped launch the utility-scale solar industry in the US, among other successes. Loan guarantees for the capital expenditures required for BiCRS facilities could significantly speed deployment.

d. **Revenue Enhancements.** For many businesses, the most valuable incentive is revenue certainty provided by enhancements. These include contracts for differences, feed-in tariffs and renewables certificates. All have been applied to biomass energy production: the UK Contract for Difference (CfD),[9] the German Energiewende on biogas[10,11] and the renewable identification numnbers (RINs) system of the US Renewable Fuel Standard.[12] None of these enhancements has included or considered CO_2 removal and disposal as a qualification to receive these enhancements nor have enhancements been designed with BiCRS in mind.

e. **Government Procurement.** In many countries, government procurement makes up more than 10% of GDP.[13] Government purchases can play an important role in starting and building new product markets. First, government purchase contracts can provide developers and manufacturers of new products with an assured market, which can be especially important in securing debt capital. Second, government purchases can help establish standard technical specifications for new products, which can help catalyze efficient supply chains. Governments could buy products made at BiCRS facilities, such as biofuels or hydrogen, or purchase the CO_2 itself for underground storage.

C. Standard-setting

1. The Challenge.

BiCRS projects raise challenging issues with respect to measuring, monitoring and crediting carbon removal. These issues involve a complex interplay of scientific, technical, socio-economic and institutional factors. Working through these issues and then incorporating solutions into government policy—at the subnational, national and international levels—will be essential for BiCRS to scale.

The principal objective of a BiCRS project is removing CO_2 from the atmosphere, and measuring the life-cycle emissions of a BiCRS project is therefore essential. As a preliminary matter, emissions from the production of biomass and shipment of biomass to a BiCRS facility must be determined. This process is similar to analyzing the life-cycle emissions of many types of products and is not conceptually challenging, although reliable data collection may be difficult or expensive. For BiCRS projects using biomass feedstocks such as sawmill waste and agricultural residues, a standard lifecycle assessment of this kind will be sufficient

BiCRS projects that use some other feedstocks present greater challenges. Dedicated energy crops and timber raise important issues with respect to land-use changes. Complications arise because the use of land to grow energy crops or timber for BiCRS projects may lead to clearing of forests—either where the energy crops or timber are grown (direct land-use change) or in distant places (indirect land-use change). This forest clearing or other land-use patterns could increase emissions, offsetting the benefits associated with the BiCRS project.

Measuring land-use changes requires consideration of socio-economic and institutional factors, potentially including data concerning land-use patterns, crop prices globally and legal regimes in specific locations. Satellites are increasingly able to provide regular, high-resolution information concerning land-use changes, however not yet with the coverage required in all circumstances.

One critical issue is the time frame in which to measure carbon neutrality. If timber is burned and takes 40 years to grow back, is that process carbon neutral? How should the risk of forest fires or other forest loss during those 40 years be addressed? (Offset insurance schemes are one approach to addressing this problem.)[14]

(The EU allows forest bioenergy under its Renewable Energy Directive only if the carbon is sourced in compliance with sustainability criteria that include forest protections. These criteria prohibit use of biomass from any country not party to the Paris Agreement unless "management systems are in place at forest sourcing area level to ensure that carbon stocks and sinks levels in the forest are maintained or strengthened over the long term."[15])

Another issue is possible leakage of CO_2 from underground storage. CO_2 can be sequestered underground with minimal leakage for centuries; however, monitoring is required for confidence that a BiCRS project's intended benefits are being realized. Although rules exist to deal with operational liabilities and post-injection site care in some jurisdictions, additional statutes are needed to define the obligations and liabilities associated with the unlikely case of CO_2 leakage.[16-19]

Crediting for carbon removal can create some conceptual challenges, especially when biomass is being shipped internationally to a BiCRS facility. Which country should receive the credit for the carbon removal? Which should be charged for any emissions related to harvesting the feedstock?[20, 21]

Developing standards in all these areas will be a multi-year process. In several areas, extensive work by scientific and technical experts are required to develop protocols and methodologies. The next step will include bottom-up incorporation of these standards into national legislation, providing an experience base to allow identification of additional issues and any problems as they arise. Some topics can be addressed within the technical and subsidiary bodies of the UN Framework Convention on Climate Change (UNFCCC) as well. The UNFCCC could create a BiCRS platform similar to its REDD+ Platform[22] as a venue for international dialogue and standard-setting related to BiCRS. This could provide a foundation for groups of countries to agree on standards for BiCRS processes—in particular those that involve international trade.

2. Global biomass trade today: an example

The global trade in biomass today highlights the important role of standard-setting with respect to BiCRS. Over 22 million tons of wood pellets for electric power generation and heating were traded internationally in 2018. The largest consumer was the UK, importing approximately one third of the market, followed by Denmark and the Republic of Korea (see Figure 5.1). These imports are largely driven by national energy policies designed to reduce greenhouse gas emissions. For example, the UK Renewable Obligations (RO) policy requires large electric generators to provide a percentage of their generation from renewables.[23] Generation from the combustion of solid biomass, such as wood pellets, is deemed by the UK government to meet the sustainability criteria of the scheme.[24] As a result, UK electricity generators (notably the Drax Power Station) have imported large amounts of wood pellets to replace coal as a fuel.

The Netherlands offers another notable example. The Dutch government provided subsidies for the use of solid biomass to generate power and heat beginning in 2018, and imports of wood pellets for these purposes grew six-fold.[25] Initially, the use of biomass was deemed to meet the sustainability criteria for the purposes of the subsidy, similar to the UK policy. However, a July 2020 report from a Dutch government advisory board recommended that this be changed, arguing that combusting solid biomass for power and heat not be considered sustainable.[26] The Dutch government is now reconsidering its approach to the classification of biomass energy production sustainability, and private actors are reconsidering investment plans.[27]

In Japan, the government has set a national target of achieving 3.7-4.6% of total power generation in 2030 from biomass, with the majority of this based on forest biomass (equivalent to 2.7 to 4.0 GW of biomass-based generation[28]). This target is supported with a feed-in tariff (FiT) subsidy policy, which has led to rapid growth of wood pellet imports for co-firing with coal, primarily from Canada and Vietnam.[29] Japan and South Korea are estimated to be the largest growth markets for wood pellet imports over the next five years.[30] Notably, the Japanese government is currently reviewing its sustainability criteria for these biomass sources.[31] We estimate that Japan's biomass power target will require 140,000,000 tons of wood per year and would create about 250 million tons of CO_2, almost all of which could be captured in state-of-the-art BiCRS systems.

These examples illustrate the different viewpoints that national governments have taken about the extent to which biomass used for power and heat can be considered sustainable, even in the case of identical biomass types (commodity solid wood pellets). While some aspects of this diversity of views can be ascribed to remaining uncertainties about the supply chain, the primary cause is different interpretations of the concept of sustainability and the time scale over which it should be measured. As a result, there is uncertainty and international misalignment about the use of biomass in energy applications as a sustainability policy.

Unless and until these viewpoints are better harmonized, nations will disagree on the climate implications and correct carbon accounting to use for biomass-based energy. This issue is relatively minor today given the small scale of this technology. However, if BiCRS is to scale up substantially, this issue will need to be resolved, with all nations coming to a common understanding of how to interpret the true climate impacts.

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CHAPTER 10:

FINDINGS AND RECOMMENDATIONS

FINDINGS

Finding 1: *Using biomass, several gigatons of CO_2 could be removed from the atmosphere and stored underground or in long-lived products each year.*

Existing analyses suggest 2.5-5.0 $GtCO_2$/y of global potential by midcentury without environmental damage or negative impacts on food security. This estimate is based on currently available waste biomass, working land, infrastructure, and agricultural and forestry technologies. With innovations in biomass conversion, technology-enabled biomass tracking, and agricultural and forestry practices, this figure could be even larger.

Finding 2: *Energy production is not the only way that biomass can be used in combination with carbon capture to store CO_2 underground or in long-lived products.*

Bioenergy with carbon capture and storage (BECCS) has received considerable attention in the climate change literature. But other ways to use biomass to sequester CO_2 for the long-term are emerging. They include long-lived products (*e.g.*, biochar), biomass conversion and disposal (*e.g.*, biomass to bioliquids followed by deep geological injection), and direct transfer of biomass far away from atmospheric reach (*e.g.*, deep-ocean disposal of macroalgae).

Finding 3: *Governance and accounting issues are key challenges to BiCRS and may set its practical limits.*

BiCRS approaches that do not use waste feedstocks share many of the same challenges facing nature-based approaches to carbon removal, including leakage, additionality, double-counting and permanence. Widely-accepted standards do not exist, and significant governance and accounting issues must be addressed for widespread acceptance and adoption.

Finding 4: *The carbon removal value of biomass may increasingly exceed its energy value.*

Biomass has low energy density. In contrast, biomass is effective at harvesting CO_2 from the air and converting that CO_2 into a form that is readily transported and stored. In a carbon-constrained world, the ability of biomass to harvest atmospheric carbon has a value that may exceed the value of net energy production. Biomass used in processes that sequester carbon should be viewed as valuable for this "carbon service," as well as for any energy services it provides.

Finding 5: *Many technologies and practices required for BiCRS are already mature.*

Key technology elements in BiCRS processes include drying, pelletizing, gasification, anaerobic digestion, biomass boilers, CO_2 capture and separation, and geological storage monitoring. Key practices include sustainable harvesting, biomass transportation and hybrid culture development. These mature technologies and practices are commercially available at scale today in global supply chains. Specific improvements (*e.g.*, conversion efficiency, waste handling, capital cost reductions) are likely with modest investments and additional commercial practice.

Finding 6: *A few key technologies and practices require deliberate focus to speed development and provide insight into BiCRS governance and scale-up.*

Some technologies with the potential to play important roles in BiCRS require further development. These include biomass to hydrogen conversion, modular fast pyrolysis, forest and farm monitoring and accounting (a combination of sensors, artificial intelligence and remote sensing), and genetic modification of common crops to enhance carbon uptake and durability. These technologies should be the focus of innovation policy, as part of a strategy to develop and deploy BiCRS systems in key markets. In addition, new pathways not linked to energy production (*e.g.*, bioliquid deep injection and macroalgae deep marine disposal) are in early stages but appear promising in terms of cost, scalability and technical viability.

Finding 7: *Without proper governance and standards, BiCRS could be counterproductive with respect to climate mitigation, biodiversity conservation, food security and rural livelihoods.*

Experience demonstrates that biomass cultivation, harvesting and trade can lead to ecosystem damage and poor outcomes of many kinds. Risks include permanent loss of biodiversity; damage to forests, soils and wetlands; reduction in agricultural yields; food security threats from elevated prices and loss of local food cultivation; leakage and displacement of agricultural and silvicultural production with associated carbon leakage; and marine ecosystem impacts. As BiCRS pathways grow and scale, care is required to monitor for poor outcomes, apply international standards and law, and shield vulnerable ecosystems from unsustainable and climate destructive practices.

RECOMMENDATIONS

Recommendation 1:

We introduce a new term—biomass carbon removal and storage (BiCRS). We recommend adoption of this term and the approach it reflects in considering the potential role of biomass in achieving net-zero global greenhouse gas emissions. The BiCRS framework focuses on the value of biomass for carbon removal and long-term storage underground or in long-lived products. It calls for projects that do no damage to—and ideally promote—food security, rural livelihoods, biodiversity conservation and other important values.

Recommendation 2:

We recommend that development of BiCRS technologies and projects focus first on waste biomass. Municipal solid waste, agricultural waste, forest waste and sewage are rich in carbon that recently came from the atmosphere. These resources are widely available and can support initial deployments of BiCRS while issues of appropriate and monitorable biomass production are addressed.

Recommendation 3:

We recommend a framework in which BiCRS projects start with the guiding principle "Do no harm." Biomass removal and storage can create risks related to food security, biodiversity loss, eco-colonialism and other issues. Projects should only be pursued after applying a precautionary principle, addressing any such risks and seeking co-benefits in these areas along with carbon removal from the atmosphere.

Recommendation 4:

We recommend an innovation roadmap for BiCRS, focusing on hydrogen, fast pyrolysis and selected non-energy pathways. The specifics of the roadmap, detailed above, include rapid development of large-pilots and demonstrations across both technology and practice. Since the BiCRS framework allows for transport of biomass, CO_2 or finished goods, geological storage assessment should be a formal part of technology development, especially in key biomass-producing and -exporting nations. Moreover, some pathways with substantial potential have received little support to date. We recommend R&D investments in areas including direct conversion of wet biomass, salty biomass feedstocks and conversion; new and advanced drying systems; and other "balance of facility" pathways to improved efficiency and cost reduction.

Recommendation 5:

We recommend a targeted effort to develop monitoring, reporting and verification (MRV) for BiCRS. Rapid technology changes regarding our ability to monitor and quantify biomass carbon accumulations hold enormous promise. Although the core aspects of biomass quantification are scientifically sound and reasonably understood, many critical topics require study and development. These topics include soil carbon fluxes, robust life-cycle accounting, macroeconomic leakage and ecosystem benefits. We propose a decade-long, focused effort by a set of nations to help clarify these issues and a new institutional role to gather and share scientific and commercial data of high relevance.

Recommendation 6:

We recommend a set of nations and companies lead development of the frameworks, methodologies and standards that must underlie gigaton-scale BiCRS as an industry. A subset of producing nations (including Brazil, the US, Indonesia, Malaysia and some African nations) together with consuming nations (the UK, the EU, Japan, Korea and the US) could help provide enough clarity in the years ahead. Locally sourced and converted biomass (including wastes and byproduct biomass) could lay the foundation for commercial standards for MRV and CO_2 disposal. We recommend leading companies and non-governmental institutions (e.g., IEA) launch a set of discussions and convenings, perhaps as part of the Clean Energy Ministerial or alongside the G20 meetings. The UN Framework Convention on Climate Change (UNFCCC) could launch a BiCRS Platform modeled after its REDD+ Platform as a global venue for this dialogue. Since standards for practice, accounting and sustainability will ultimately serve companies over the long-term, we recommend companies participate actively in these discussions (as some have already).