Carbon Dioxide Removal Options: A Literature Review Identifying Carbon Removal Potentials and Costs

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ABSTRACT

In 2015, nearly 190 countries came together in the historic Paris agreement to take action in minimizing the impacts of climate change. However, even with the consensus to cut carbon emissions, the continued trajectory of global emissions will push global temperatures 2°C past pre-industrial temperatures. Implementation of carbon dioxide removal (CDR) options is a way to meet the target.

Through an extensive literature review, ten CDR/storage options were examined to gain a better understanding of the current state of research regarding the CDR potential of each option and their relevant costs, as well as the feasibility of their implementation. As we have concluded that all options require significant further research, a second major objective was to highlight where major gaps in research exist in order to help guide further inquiry in CDR options.

Every option was examined extensively and presented in an individual chapter. Each chapter presents our findings regarding the CDR/storage potential and economic costs collected for each option. In addition, each chapter includes a discussion of the technical or natural process, geographic restrictions, policy implications, benefits and risks associated with the implementation, as well as recommendations for further research. The biggest takeaways from the literature review is that this set of CDR options offer enough removal potential to warrant equal consideration to other emission reduction measures, all options face limitations and uncertainties so a diverse portfolio of options should be pursued, and implementation should occur in a staged manner, in which options are implemented as they become feasible.

ACKNOWLEDGEMENTS

The graduate student research team is grateful for the support and guidance of the current and past professors and staff at the University of Michigan’s Energy Institute, especially John DeCicco, Susan Fancy, Mark Barteau, and Daniel Raimi. This project would also not have been possible without the guidance of our advisor, Professor Rosina Bierbaum. Finally, thank you to all our reviewers including but not limited to Richard Birdsey, Ik Kyo Chung, Annette Cowie, Noah Deich, Riley Duren, Sabine Fuss, Howard Herzog, Mark Hunter, David Keith, Abby Kirchofer, Klaus Lackner, Johannes Lehmann, Greg Rau, Ralph Sims, David Skole, Todd Walter, and Jennifer Wilcox.

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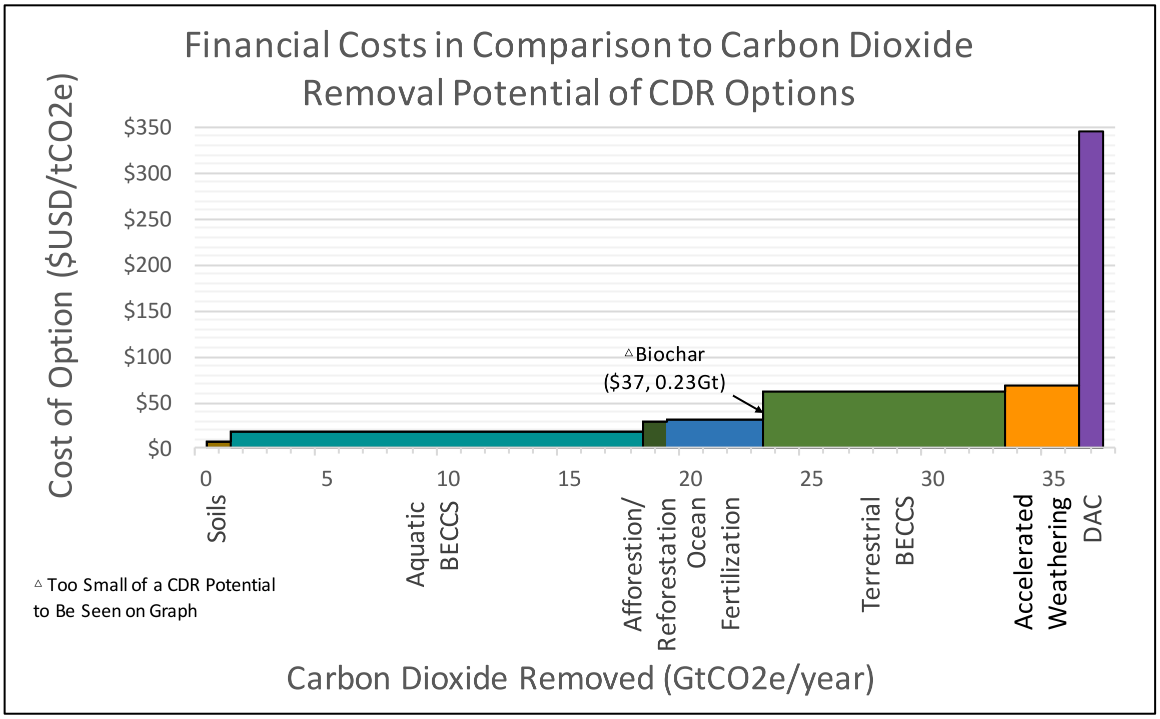


Introduction

To meet the 2°C target goals under the 2015 Paris Agreement, as well as to ameliorate concerns regarding the viability of pledges, carbon dioxide removal (CDR) options provide the potential to offset carbon dioxide (CO_2) emissions. CDR is different from other climate mitigation strategies as it aims to increase the rate of negative emissions to achieve “beyond carbon-neutral" rather than reduce net GHG emissions to zero to achieve a "carbon-neutral" state. The process of CDR can be achieved through natural processes, such as photosynthesis, weathering of silicate rock, and absorption by the ocean. Furthermore, the enhanced natural processes and development of options which capture and sequester or utilize CO_2 are required to accelerate the rate of CDR and reach negative net carbon emissions in the future.

To complement and inform efforts to reduce greenhouse gas (GHG) emissions, the University of Michigan Energy Institute is leading a major new research initiative called Beyond Carbon Neutral (BCN) that seeks to develop options, programs, and policies to increase the deployment of CDR as part of a comprehensive approach to climate change. As an important part of this initiative, a team of Master’s students from the University of Michigan School of Natural Resources & Environment was asked to compile a literature review of existing research on the financial costs of implementing eight CDR options and two CO_2 storage only options and the removal and/or storage potential of each option. This 16-month opus project plots the estimated costs of specific CDR activities against estimated CO_2 removal potential. The report also discusses the benefits, risks, geographic restrictions and policy implementation issues associated with various CDR and storage approaches and makes suggestions for future research.

Based on a literature review, the options selected for evaluation are afforestation/reforestation (AR), soil carbon sequestration, biochar, accelerated weathering, direct air capture (DAC), terrestrial bioenergy with carbon capture and storage (BECCS), aquatic bioenergy with carbon capture and storage (Aquatic BECCS), ocean storage, ocean fertilization, and carbon utilization/enhanced oil recovery (EOR). Based on current technical and economic analysis of the eight CDR options and two storage only options, they can be classified into three levels, established, demonstrated, and speculative. Established options should be estimated with a well-defined sequestration and cost measurement process of applied projects. Demonstrated options should have several pilot projects applied to small regions. Speculative options need further research and development (R&D) to justify their feasibility. Details about the definition and readiness level of each CDR and storage option can be seen from Table EX-1.

CDR Options	Definition	Readiness Level
Afforestation/ Reforestation (AR)	Afforestation/Reforestation refers to land management methodologies that involve intentional forest management techniques to sequester and store CO_2 over a prolonged period.	Established
Soil Carbon Sequestration	Soil Carbon Sequestration is a land management technique that aims to increase the amount of carbon stored in soil organic matter as well as in inorganic forms within the soil.	Demonstrated
Biochar	Biochar creates charcoal derived from biomass through a process called pyrolysis, which heats biomass to between 300°C and 800°C in a low oxygenated environment.	Demonstrated
Terrestrial BECCS	The BECCS process takes advantage of the carbon dioxide removal abilities of photosynthesis through the growth of terrestrial biomass with the additional capture of CO_2 during the production of energy products.	Demonstrated
Aquatic BECCS	Aquatic BECCS absorbs CO_2 via plant growth in the ocean and then uses the harvested aquatic biomass to generate energy with capture and subsequent storage of CO_2.	Speculative
Ocean Fertilization	Ocean fertilization purposefully introduces specific nutrients into the ocean to stimulate growth in marine organisms (phytoplankton), thus removing CO_2 from the atmosphere via photosynthesis by ocean organisms.	Speculative
Accelerated Weathering	Accelerated weathering refers to the geochemical process by which naturally-occurring carbonate and silicate weathering are accelerated on land and in marine environments.	Speculative
Direct Air Capture (DAC)	DAC systems separate CO_2 directly from the atmosphere through chemical adsorption.	Speculative
Storage Options	**Definition**	**Readiness Level**
Enhanced Oil Recovery (EOR)	EOR is the process in which captured CO_2 is injected into oil wells which are nearing the end of their productive lives.	Established
Ocean Storage	This process stores CO_2 within the shallow waters of the sunlit zone or in deep pockets of the ocean.	Speculative

Table EX-1: Readiness characterization of the ten CDR and storage options.

Methodology

This study is a comprehensive literature review of estimates of the CDR/storage potential and the cost of said removal for eight CDR options and two storage only options. The following procedures were conducted on all ten options.

Literature Review: A literature review was conducted for each technology starting with the National Resource Council (NRC) report "Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration" (2015) report and following references forward and backward to identify related studies. Each article was analyzed specifically for CDR/storage potential estimates as well as for cost figures for the related option. Additional information was gathered regarding the current state of the option, variations in implementation, barriers to scaling the options, interactions between the options, and policy implications.

Data Extraction: Any articles that indicated CDR/storage potential or cost figures, whether from empirical research, modeling, or meta-analysis, were extracted and included in our database in their original units. If an article presented multiple estimates, a low, medium, and a high figure was extracted from the article.

Data Conversion: Based on the original units, each article's CDR/storage estimates were converted into $GtCO_2e$/yr and each article's cost estimates were converted into 2015 USD/ tCO_2e. See Chapter 2 of this report for the assumptions made during the data conversion process.

Data Analysis: After all data was converted to standardized CDR/storage and cost units, the data was further analyzed using descriptive statistics. When a sufficient number of independent estimates were available, a quartile analysis was conducted to determine the minimum, 1st quartile, 2nd quartile (median), 3rd quartile, and maximum estimates. Unless otherwise noted, median estimates represent the CDR/storage potential and cost estimates. This analysis was conducted to determine the distribution of estimates. Note this analysis is solely for descriptive purposes and the estimates generated from this analysis are not inferential statistics.

Review: Academic and professional experts on each option were consulted through conferences and direct communication for a review of initial results and recommendations regarding additional data and considerations that should be included in the final analysis. The feedback from experts was assessed and incorporated into our database.

Chapter Reporting: Finally, graphs and chapters were created to analyze each option as well as to compare standardized CDR potential and cost estimates across the ten CDR and storage options.

Results

The results of the literature analysis are presented below. Each of the ten options are first analyzed individually discussing the estimated range and median CDR/storage potential and cost. Additionally, any key benefits, challenges, risks, and further research needs are discussed. Finally, the carbon dioxide removal potential and cost results from each technology are compared, discussed, and presented in tables and graphs.

Carbon dioxide removal (CDR) rates are reported in billions of metric tons, CO_2-equivalent, per year ($GtCO_2e$/yr, i.e., $10^{15}gCO_2 \cdot yr^{-1}$). To put these values into context, the gross circulation of the global carbon cycle amounts to 64.5 $GtCO_2e$/yr, of which 17.2 $GtCO_2e$/yr is the terrestrial carbon cycle, and 11 $GtCO_2e$/yr is carbon exchange between the oceans and the atmosphere. Of the 34 $GtCO_2e$/yr from anthropogenic emissions, 18 $GtCO_2e$/yr is sequestered by natural processes and 16 $GtCO_2$/yr remains in the atmosphere.

Afforestation and Reforestation

Afforestation and Reforestation (AR), an established CDR option, is a commonly referenced land management methodologies that removes CO_2 from the atmosphere through photosynthesis and store the carbon within forest biomass. Based on literature, afforestation/reforestation has the potential to capture and store between 0.01 – 14 $GtCO_2e$/year at a cost between \$2 - \$100/tCO_2e. The median values of this wide range suggest an approximate CDR potential of 1.1 $GtCO_2e$/year at \$30/tCO_2e. Although afforestation/reforestation has benefits such as creating additional ecosystem services, its major challenge is the question of permanence, related to natural disasters and deforestation as well as competition over land area. Further research is necessary to refine the estimates of AR CDR potential and cost for specific regions.

Soil Carbon Sequestration

Soil carbon sequestration, a demonstrated CDR option, entails management of pastures and cropland to increase the carbon stored in the soil. Based on current literature, soil carbon sequestration has the potential to capture and store between 0.1 – 13 GtCO2e/year at a cost between \$5.50 -\$11/tCO_2e. The median CDR potential is 1.3 $GtCO_2e$/year. Our evaluation of the literature suggests an approximate cost of \$8/tCO_2e. However, cost estimates were limited to the literature, and therefore cannot be accurately forecasted at this time. Because soil carbon sequestration is based on the natural carbon cycle, challenges exist in measuring the net carbon sequestered over large areas and ensuring its permanence in the soil. Future research is needed on the incremental cost of carbon sequestration above baseline land management techniques across the wide range of soil and crop types that can be used for this technology.

Biochar

Biochar, a demonstrated CDR option, is produced when biomass, which takes in carbon through photosynthesis, is heated to between 300°C and 800°C in a low-oxygen environment. The end product is a carbon-rich char, commonly known as charcoal. This char can then be used as a soil amendment and has been used for thousands of years by some pre-industrial agricultural communities. Biochar is considered a form of carbon storage because the char decomposes much slower than the surrounding biomass when added to soils. Based on current literature, biochar has the potential to capture and store between 0.03 – 1 $GtCO_2e$/year at a cost between $(150) - $670/$tCO_2e$. The negative costs at the low end refer to the net gain that can be seen by farmers with the increases in crop yields. The median of this range is 0.2 $GtCO_2e$/year at an approximate cost of $40/$tCO_2e$. Although low-tech techniques to produce biochar have been around for millennia, research is underway to develop technologies for efficient large-scale production. The greenhouse gases released during the production process could become significant for large-scale production. There is also a limit to the amount of biochar that can be added to soils, and in some cases, biochar was shown to have adverse effects on crop yields. Continued research is needed to determine which feedstock, the temperature in the production process, and application rates to soils produce the best results for different soil types. This research would make biochar application to agricultural lands more attractive.

Accelerated Weathering

Accelerated weathering, a speculative CDR option, is a set of CO_2 removal techniques that accelerate the chemical reaction of CO_2 with silicate-based minerals such as olivine, serpentine, and wollastonite. In-situ accelerated weathering involves exposing these minerals to atmospheric gases over a large land area. Alternatively, carbon mineralization mixes industrial waste such as cement kiln slag or coal fly ash with CO_2 in a saline solution in a controlled reaction facility. Based on current literature, accelerated weathering has the potential to capture and store between 0.001 – 18 $GtCO_2e$/year at a cost between $20 - $540/$tCO_2e$, with median estimates of 3.7 $GtCO_2e$/year at $70/$tCO_2e$. Additional research is needed to understand the environmental impact of in-situ accelerated weathering and to bring pilot carbon mineralization projects to scale. Furthermore, studies focused on accelerated weathering potential should evaluate the cumulative potential of all accelerated weathering techniques.

Direct Air Capture (DAC)

DAC, a speculative CDR option, involves the use of man-made structures to capture CO_2 from ambient air and concentrate it through chemical bonding. Bonds are formed by either an aqueous solution or a porous ion charged solid filter. While these systems are undergoing engineering development, no large-scale demonstration project has been undertaken. Based on current literature, DAC has the potential to capture and store between 0.0004 – 16 $GtCO_2e$/year at a cost between \$30 - \$1,050/tCO_2e. Wide variances in the removal potential and economic estimates exist due to the largely speculative nature of DAC and the range of assumptions used in the studies. DAC has a median cost of \$345/tCO_2e a selected number for comparative purposes for removal potential of 1 $GtCO_2e$/yr.

DAC benefits from a small geographic footprint compared to other CDR options and can be built near geologic storage options to reduce transport costs. The high cost of capture is a significant challenge to overcome and is attributed to high energy requirements. There is a consensus that DAC will not be a feasible option until mid-century after the energy sector has been de-carbonized. Future research is needed to create bonds that can better attract CO_2 molecules and require less energy to break the bonds.

Terrestrial Bioenergy with Carbon Capture and Storage (BECCS)

BECCS, a demonstrated option, harvests biomass for conversion into electricity or biofuels through combustion, gasification, fermentation or other processes. The biogenic CO_2 released during combustion and processing is captured rather than emitted to the atmosphere using technologies like those designed for fossil fuel carbon capture and storage (CCS). Based on current literature, BECCS has the potential to capture and store between 0.04 – 32 $GtCO_2e$/year at a cost between \$20 and \$440/tCO_2e. Extracting more than 12 $GtCO_2$ from the atmosphere a year results in large increases in costs. The median values of BECCS CDR potential and costs are 9 $GtCO_2e$/year at \$60/tCO_2e.

The technology for generating electricity and capturing CO_2 from power plants already exists and BECCS benefits from those previous investments. BECCS is widely assumed in integrated assessment model (IAM) scenarios that simulate ways to limit global warming to 2°C. There is concern about dedicated energy crops increasing food prices and decreasing biodiversity. BECCS has come under scrutiny recently as questions emerge about whether BECCS is carbon negative, neutral or positive. Future research should focus on understanding land use change, creating a more robust carbon accounting of the BECCS process, and improving the viability of future generation biomass feedstocks.

Aquatic Bioenergy with Carbon Capture and Storage (Aquatic BECCS)

Aquatic Bioenergy with Carbon Capture and Storage (Aquatic BECCS) is a speculative CDR option that absorbs CO_2 via plant growth in the ocean and then uses the harvested aquatic biomass to generate energy with the capture and subsequent storage of CO_2. Based on current literature, Aquatic BECCS has the potential to capture and store between 1.2 – 53 $GtCO_2e$/year at a cost between \$18 - \$140/tCO_2e. Aquatic BECCS has a median potential to capture and store 18 $GtCO_2e$/year. Additionally, an approximate cost of \$18/tCO_2e seems the most plausible. Compared to the other seven CDR options examined in this report, very little theoretical and empirical research has been conducted on Aquatic BECCS. Further research regarding implementation impacts such as ecological and industry impact, economic costs, and CDR potential of Aquatic BECCS is necessary before mass implementation.

Ocean Fertilization

Ocean fertilization, sometimes known as ocean nourishment, is a speculative CDR option that purposefully introduces specific nutrients into the ocean to stimulate growth in marine microscopic organisms (phytoplankton), thus speeding up the rate at which CO_2 is removed from the atmosphere via photosynthesis by ocean organisms. Based on current literature, ocean fertilization has the potential to capture and store between 1 – 11 $GtCO_2e$/year at a cost between \$10 - \$290/tCO_2e, with median estimates of 4 $GtCO_2e$/year at an approximate cost of \$30/tCO_2e. A claimed benefit of ocean fertilization is it will not compete for land. However, little is known about large-scale, long-term impacts of adding millions of tons of iron, nitrogen, or phosphorous to the ocean. Additional research on the impacts of large-scale ocean fertilization implementation as well as the sequestration and storage efficiency and potential is imperative before governments consider promoting an ocean fertilization initiative.

Carbon Storage Options

In addition to the 8 CDR options, two storage options were researched, ocean storage and enhanced oil recovery (EOR). CDR options such as BECCS, Aquatic BECCS, and DAC capture CO_2 but do not offer a storage mechanism, so storage options play a vital role in negative emissions. Other geologic storage options such as saline aquifers, depleted coal seams, basalt formations, and offshore sediments are briefly discussed in Chapter 11 but were not part of the literature review.

Ocean Storage

Ocean storage is not a form of carbon removal. It is only a means to store carbon for long periods of time. It can be as complex as processing and pumping liquid, gas, or solid CO_2 into deep pockets of the oceans, or as simple as dumping crop residue off the side of a ship. Based on current literature, ocean storage has the potential to capture and store between 0.01 – 0.9 $GtCO_2e$/year at a cost between \$15 - \$270/tCO_2e. Considering current infrastructure and existing technology, we assume that dumping crop residue directly into the deep ocean is the most plausible form of ocean storage for the near future. In this case, the estimated storage potential is 0.55 $GtCO_2e$ at the cost of approximately \$26/tCO_2e. A benefit of ocean storage is the wide geographic area where is could be implemented. However, little is known about what the effects of storing carbon are on deep sea ecosystems. Currently, the potential for unintended consequences outweigh the benefits of storing carbon in this way. Research is needed to determine what these effects may be and if they pose a significant threat to aquatic life.

Carbon Utilization

Carbon utilization recognizes that CO_2 can be a valuable resource for industry. Instead of injecting CO_2 into a geologic storage facility, CO_2 can be used as an input in other products such as carbonated beverages, refrigerants, chemicals, and plastics. One of the only established carbon utilization options which provides permanent storage for captured CO_2 is enhanced oil recovery (EOR). EOR pumps concentrated CO_2 into depleted oil wells and displaces oil in the pores of the sediment to increase crude oil production. Based on current literature, carbon utilization in the form of EOR has the potential to cumulatively store between 0.05 – 370 $GtCO_2e$ at a price between \$17 - \$50/tCO_2e. A selected number for comparative purposes to other CDR options for carbon storage potential is 65 $GtCO_2$, an estimate that considers the entire world and limits storage to sites within 800 km of CO_2 capture facilities. On the economic side, a price of \$40/tCO_2 was selected due to its prevalence in the literature.

The biggest benefits for EOR are that it provides revenue for CO_2 capture activities and could help kick-start CO_2 capture at a commercial scale. Additionally, EOR can benefit from the investment oil companies have already sunk into these wells. There are human and environmental health concerns regarding the injection of concentrated CO_2 into depleted oil wells and future research should focus on alleviating these concerns.

CDR Option Comparison

The CDR options discussed cover all aspects of CO_2 removal treated in the literature we reviewed. The options cover terrestrial and aquatic, above-and-below-ground, simple and complex, and ready to implement today and futuristic options. The biggest takeaways from the literature review is that this set of CDR options offer enough removal potential to warrant equal consideration to other emission reduction measures, all options face limitations and uncertainties so a diverse portfolio of options should be pursued, and implementation should occur in a staged manner, in which options are implemented as they become feasible. Terrestrial options such as AR, accelerated weathering, and BECCS require large amounts of land. The aquatic CDR options and DAC can help offset some of the land requirements. High-cost options such as DAC can be strategically implemented and low-cost options such as AR can offset costs. As these CDR options will be working in tandem, it is important to understand the comparative economics and CO_2 removal potential. Table EX-2 provides a synthesis of the carbon dioxide removal potential of each CDR option and Table EX-3 provides a synthesis of the economic estimates of each CDR option. Graph EX-1 visually depicts the range and median/selected value for carbon dioxide removal and storage potential. Graph EX-2 visually depicts the range and median/selected value for the economic estimates. Graph EX-3 visually depicts the removal potential and economic estimates for the eight CDR options.

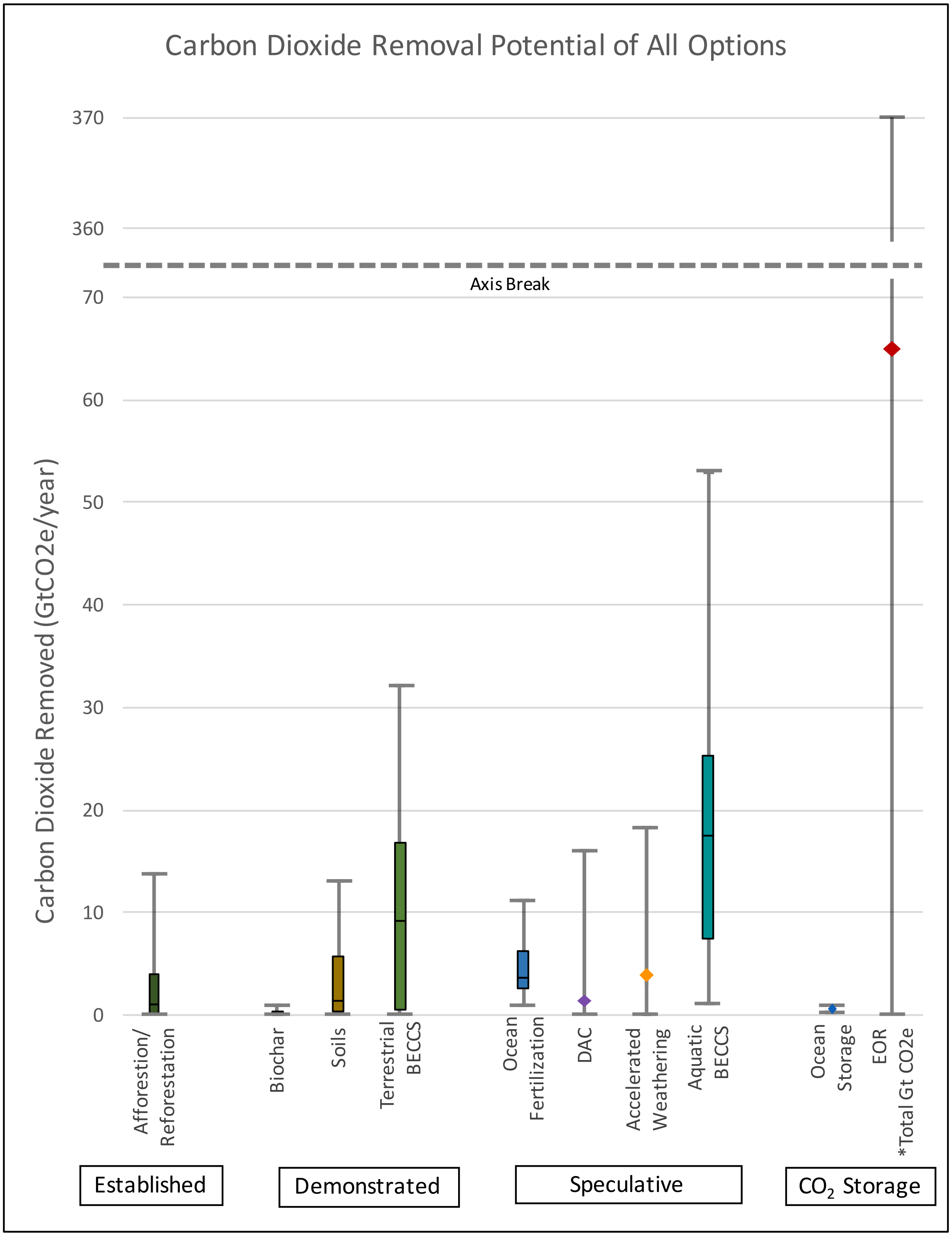
The established options include EOR and AR. Since AR is a CDR option and EOR a storage option, they cannot be compared. Among the demonstrated CDR options, the magnitude of CDR potential identified for BECCS appears to greatly exceed that of soil carbon sequestration and biochar; however, this impression is due to the highly speculative large-scale BECCS implementation that has been simulated in many IAM scenario analyses. Regarding cost, soil carbon sequestration appears to be the least expensive option with its very tight and low range of published economic estimates. The cost range for biochar and BECCS varies by \$400/tCO_2e or more; costs at the high end of such a range would preclude those options from being commercially viable. Biochar offers the added benefit of generating revenue through improved crop productivity, which is why the low end of its estimates includes a negative cost. The speculative options vary greatly regarding the carbon removal potential. In general, all speculative options have modest low and median/selected values and, with the exception of ocean storage, have large maximum estimates. On the economic side, for the exception of DAC, the low and median/selected values all fall into a commercially feasible range. The maximum values for each option would exceed commercially feasibility. DAC has the largest economic range of all the options and is only commercially feasible at the minimum value.

CDR Option	Carbon Dioxide Removal Potential ($GtCO_2e$/year)			
	Minimum	Median or [Selected]	Maximum	Number of Estimates
Afforestation and Reforestation	0.01	1.1	14	21
Soil Carbon Sequestration	0.1	1.3	13	23
Biochar	0.03	0.2	1	15
Accelerated Weathering	0.001	[3.7]	18	11
Direct Air Capture	0.0004	[1]	16	9
Terrestrial BECCS	0.04	9	32	23
Aquatic BECCS	1.2	18	53	14
Ocean Fertilization	1	4	11	17
EOR *Cumulative Storage CO_2e*	0.05	[65]	370	14
Ocean Storage	0.01	[0.55]	0.9	3

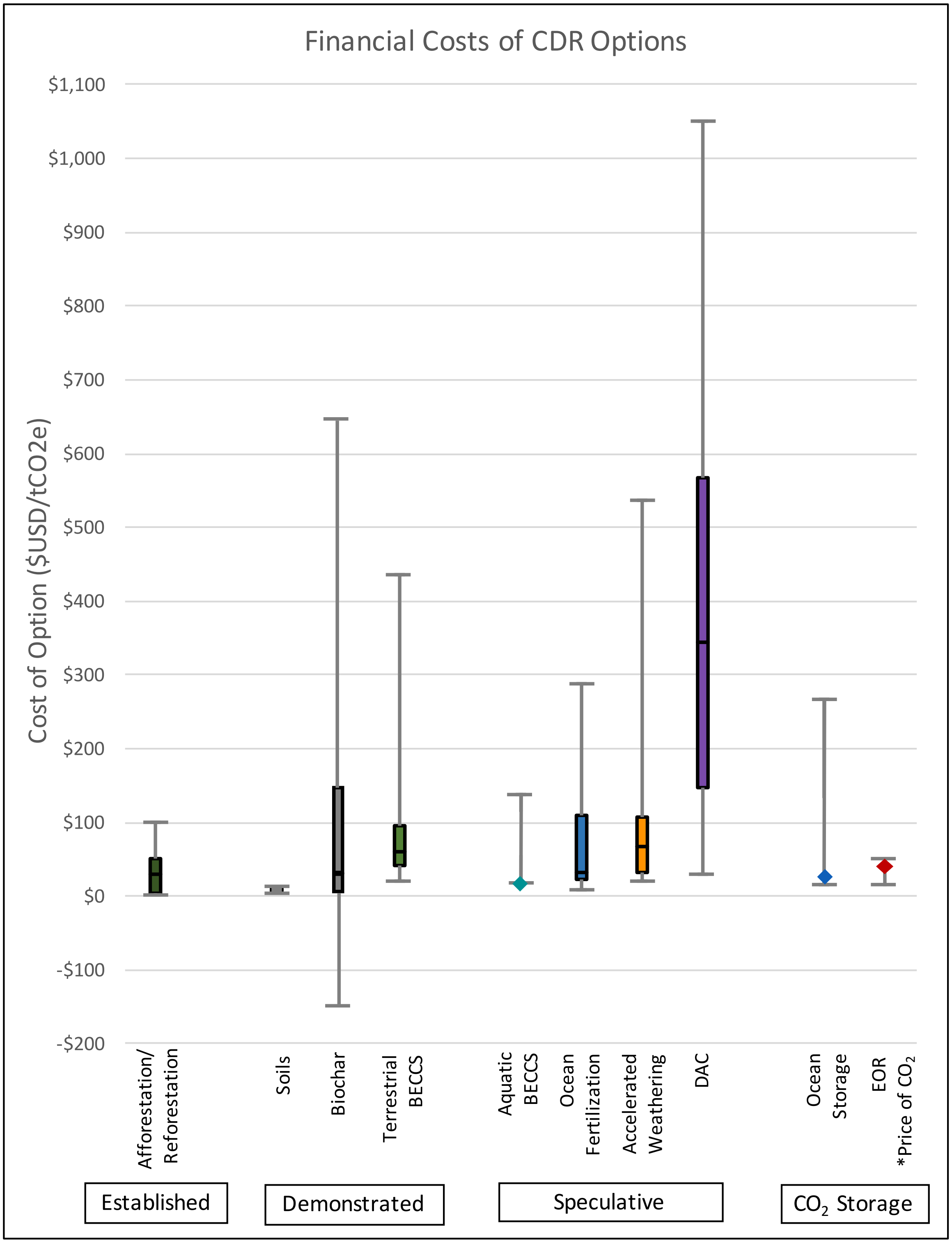
Table EX-2: Synthesis of carbon dioxide removal potential for ten CDR and storage options.

CDR Option	Cost of Option ($USD/$tCO_2e$)			
	Minimum	Median or [Selected]	Maximum	Number of Estimates
Afforestation and Reforestation	2	30	100	9
Soil Carbon Sequestration	5.5	[8]	11	1
Biochar	-150	40	670	40
Accelerated Weathering	20	70	540	14
Direct Air Capture	30	345	1,050	22
Terrestrial BECCS	20	60	440	20
Aquatic BECCS	18	[18]	140	3
Ocean Fertilization	10	30	290	11
EOR *Price of CO_2e*	17	[40]	50	5
Ocean Storage	15	[26]	270	13

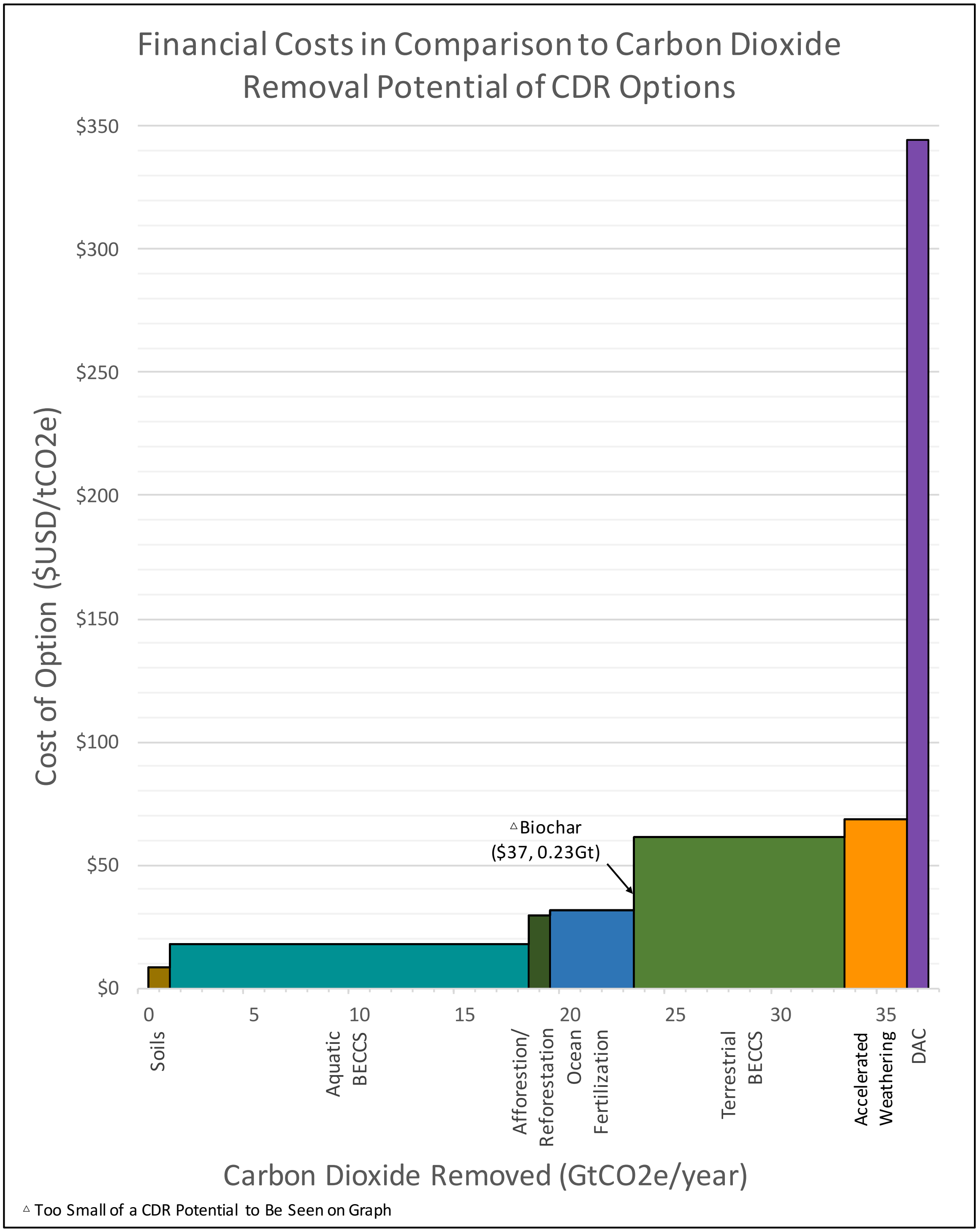
Table EX-3: Synthesis of economic estimates for ten CDR and storage options.



Graph EX-1: Carbon dioxide removal potential across the ten CDR and storage options.



Graph EX-2: Economic estimates across the ten CDR and storage only options.



Graph EX-3: Comparison of removal potential and economic estimates for eight CDR options.

Chapter 1:

Introduction

Introduction

Background

In 2015, nearly 190 countries came together in the historic Paris agreement to take action in minimizing the impacts of climate change. While a major step forward, the pledged carbon emission reductions equate to an estimated global warming increase of 2.7°C (Van Asselt, 2016). Since the Kyoto Protocol baseline year of 1990, carbon emissions have continued to rise to 34 $GtCO_2$ per year (NRC, 2015). This trend has triggered concerns that countries will not be able to meet the necessary emissions reduction goals to meet the 2°C target set forth in the Paris Agreement (Burleson, 2016).

To bridge the gap between pledged and necessary emissions reductions, as well as, to ameliorate concerns regarding the viability of pledges, other solutions to reduce atmospheric carbon dioxide (CO_2) levels must be explored. In conjunction with CO_2 emission reductions, carbon dioxide removal (CDR) options have the potential to provide the necessary CO_2 offsets to meet the Paris Agreement goals. What distinguishes CDR from other climate mitigation strategies is that CDR aims to increase the rate of negative emissions beyond carbon neutral rather than reduce net GHG emissions to zero to achieve a "carbon-neutral" state. Natural processes such as photosynthesis by vegetation, weathering of silicate rock, and absorption by the ocean already remove CO_2 from the atmosphere. However, the accelerated rate of CDR through enhanced natural processes and development of options which capture and sequester or utilize CO_2 is necessary to reach negative net carbon emissions.

CDR rates are reported in billions of metric tons, CO_2-equivalent, per year ($GtCO_2e/yr$, i.e., $10^{15} gCO_2 \cdot yr^{-1}$). To put these values into context, the gross circulation of the global carbon cycle amounts to 64.5 $GtCO_2e/yr$, of which 17.2 $GtCO_2e/yr$ is the terrestrial carbon cycle and approximately 11 $GtCO_2e/yr$ is carbon exchange between the oceans and the atmosphere (IPCC, 2013). Of the 34 $GtCO_2e/yr$ from anthropogenic emissions, 18 $GtCO_2e/yr$ is sequestered by natural processes and 16 $GtCO_2/yr$ remains in the atmosphere.

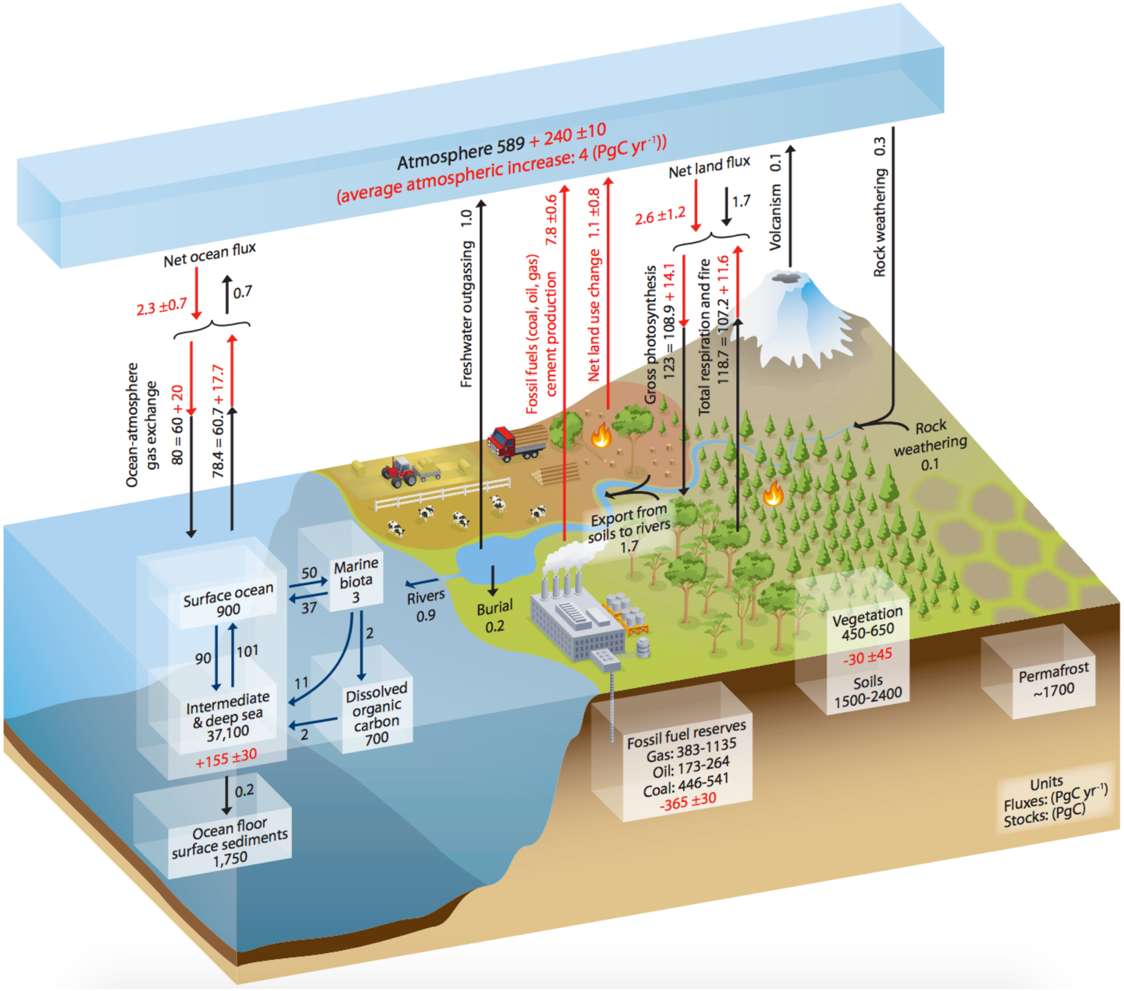


Figure 1-1: Global carbon cycle. Fluxes are presented in GtC/yr. Black numbers represent natural fluxes whereas red numbers represent anthropogenic fluxes. Image from IPCC, 2013.

Project Goals

To complement and inform efforts to reduce greenhouse gas (GHG) emissions, the University of Michigan Energy Institute is leading a major new research initiative called Beyond Carbon Neutral (BCN) that seeks to develop options, programs, and policies to increase the deployment of CDR as part of a comprehensive approach to climate change. As an important part of this initiative, a team of Master's students from the University of Michigan School of Natural Resources & Environment was asked to compile a literature review of existing research on the financial costs of implementing eight CDR options and two CO_2 storage only options and the removal and/or storage potential of each option. This 16-month opus project plots the estimated costs of specific CDR activities against estimated CO_2 removal potential. The report also discusses the benefits, risks, geographic restrictions and policy implementation issues associated with various CDR and storage approaches and makes suggestions for future research.

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Ocean Storage	This process stores CO_2 within the shallow waters of the sunlit zone or in deep pockets of the ocean.	Speculative

Table EX-1: Readiness characterization of the ten CDR and storage options.

Based on existing literature, the ten options selected for review are afforestation/reforestation (AR), soil carbon sequestration, biochar, accelerated weathering, direct air capture (DAC), terrestrial bioenergy with carbon capture and storage (BECCS), aquatic bioenergy with carbon capture and storage (Aquatic BECCS), ocean storage, ocean fertilization, and carbon utilization/enhanced oil recovery (EOR). Based on the existing estimates of their technical and economic feasibility, these options are at different readiness levels, which are identified as established, demonstrated, and speculative. Options classified as established refers to the ones with an abundance of applied and scaled projects with a well-defined sequestration and cost measurement process, although some technological problems may remain depending on the regional application. As there are many organizations and governments globally engaged in AR initiatives to create forests and EOR has been utilized on oil fields for decades, these two options can be viewed as established. Soil carbon sequestration, biochar, and BECCS are at the demonstrated stage, which notes that there have been several integrated pilot systems in an operational environment of some regions. The remaining five options are classified as speculative, including DAC, Aquatic BECCS, ocean storage, ocean fertilization, and accelerated weathering. Speculative implies these approaches are at early stages of development and need time for research to determine their feasibility, suggesting further studies and continuous lab measurements are required. It's not surprising that half of the CDR and storage options are speculative as most economic and removal potential estimates for these options are based on modeling and major assumptions.

Carbon Dioxide Removal Options

Afforestation and Reforestation

Afforestation and Reforestation, an established CDR option, are commonly referenced land management methodologies that involve intentional forest management techniques to sequester and store CO_2 over a prolonged period. Afforestation is the process of foresting land that never contained forests or restoring land that has been deforested over 50 years ago. Reforestation is the process of restoring land to a forested state that has been deforested less than 50 years ago (NRC, 2015). Through the photosynthesis process, trees take in CO_2 from the atmosphere, store the carbon within their trunk, branches, stems, and roots, and then release oxygen back into the atmosphere (Vashum & Jayakumar, 2012).

In 2013, forest land occupied 30.9% of the world's land area, compared to 37.7% of world land area devoted to agricultural purposes (World Bank, 2016). The total forest area declined from 4,128 million hectares in 1990 to 3,999 million hectares in 2015 (MacDicken et al., 2016). While natural forest areas continue to decline, planted forest area is increasing, having increased by over 110 million hectares between 1990 and 2015 (MacDicken et al., 2016). Forests, although thought of as a natural sink for CO_2, can easily become a source of CO_2 through deforestation (NRC, 2015). Although the amount of GHG emissions from deforestation is decreasing, emissions in 2010 directly related to deforestation were approximately 3.7 $GtCO_2e$ (FAO, 2014). Reducing this source of CO_2 emissions while creating additional CO_2 sinks will play a critical role in reducing global net GHG emissions.

Afforestation/reforestation is directly related to some of the other CDR options. For example, as trees take in CO_2 from the atmosphere and store the carbon within their biomass, some of that carbon will be stored within the soil. Similar processes and storage occur with soil carbon sequestration and Terrestrial BECCS. Additionally, one of the major challenges afforestation/reforestation will and is currently facing is competition over land use with urban development, agriculture, as well as, other CDR options. Afforestation/reforestation, soil carbon sequestration, and Terrestrial BECCS will all be direct land competitors when deciding which CDR option to implement.

Soil Carbon Sequestration

Soil carbon sequestration, a demonstrated CDR option, is a land management technique that aims to increase the quantity of carbon stored in soil organic matter, as well as, in inorganic forms within the soil. While soil can be either a source or sink of carbon, techniques such as cover cropping, no-till, reduced fallow, and increased perennial crops can improve soil's ability to hold carbon in crop and grazing land (Eagle, 2012). Other soils in grasslands, forests, wetlands, and tundra also form part of the overall potential for soil to remove CO_2 from the atmosphere through targeted land management. As a CDR option, soil carbon sequestration is a demonstrated CDR approach with a high degree of variability in outcomes due to ecological system dynamics. Adding to this, the challenge of balancing yield maximization with carbon storage makes soil carbon sequestration a complex option with high levels of uncertainty. Soil carbon sequestration is easily reversed through changes in land management, so CO_2 removed from the atmosphere is sequestered on a scale of decades to centuries.

Biochar

Biochar is a demonstrated CDR option based on products derived from biomass through a process called pyrolysis, which heats biomass to between 300°C and 800°C in a low oxygenated environment. This process can be classified as fast pyrolysis or slow pyrolysis, with respect to the higher processing temperature and shorter biomass residence time in the former one. Biochar is primarily used for soil abatement with the aim of improving soil structure while increasing water and fertilizer retention. It is now being considered for use as a form of carbon sequestration as biochar can decompose much slower than the surrounding biomass when added to soils. Besides, in conjunction with the production of biochar through pyrolysis, the bioenergy products, such as syngas and bio-oil, could provide alternative energy sources for electricity generation and heating application and further reduce CO_2 (Kung et al., 2013). However, due to the high uncertainty in the characteristics of biochar in different regions, further research is needed to determine the net gain or loss of CO_2 in soil biota with the use of biochar (Lehmann et al., 2011). Uncertain factors include potential CO_2 emissions reduction, the types of biomass (crops or waste), or energy sources of the pyrolysis system (Dickinson et al., 2015).

In a nutshell, compared with the other CDR approaches, biochar has existing fundamental and first-hand research regarding its viability, benefits, costs, and carbon removal potential. However, continued research is still needed to identify and understand the large number of variables that go into biochar implementation and production.

Accelerated Weathering

Accelerated weathering, a speculative CDR option, refers to the geochemical process by which naturally-occurring carbonate and silicate weathering is accelerated on land and in marine environments. Forms of accelerated weathering are sometimes referred to as enhanced weathering and carbon mineralization. The process requires that either a concentrated flow of CO_2 be mixed with a silicate-based compound or that the compound be spread over large areas of land or sea to allow atmospheric CO_2 to react with the compound and form bicarbonate ions and calcium carbonate solids (NRC, 2015). Accelerated weathering includes both in situ and ex situ sequestration and storage. Recent experiments in Iceland and the United States have explored the opportunity to store CO2 in basalt and peridotite formations through in situ mineral carbonation. This creates the opportunity to combine accelerated weathering as a storage option with other sequestration only options such as direct air capture.

Direct Air Capture (DAC)

Direct Air Capture (DAC) is a speculative CDR option. DAC systems separate CO_2 directly from the atmosphere through chemical adsorption. The two DAC systems discussed in the literature are aqueous chemical sorbents or solid sorbents. Both systems take advantage of CO_2 bonding to collect CO_2 and subsequent bond breaking to produce a concentrated form of CO_2 that is ready for transport and storage. Proposed aqueous solution DAC systems use hydroxides to facilitate CO_2 capture and the proposed solid sorbent DAC system uses negatively charged carbonate ions which attach CO_2 molecules to nanopores of the solid filter. Much of the literature is based on models or building hypothetical DAC systems from existing options in related but separate industries. The assumptions used in conjunction with the relative future focused DAC implementation timeframe contribute to wide variances in the DAC estimates.

Large scale DAC implementation has the potential to reduce atmospheric CO_2 without major environmental impact due to its limited land area required for operation and limited effect on the surrounding environment (Mazzotti, 2013). However, several significant challenges must be addressed before DAC can move towards becoming an established option. DAC systems use a large amount of energy. To amass significant CO_2 reductions, carbon-free energy is needed. One of the biggest advantages of solid sorbent systems to aqueous solution DAC systems is reduced energy consumption. This is due to reduced energy costs of breaking CO_2 bonds in a solid filter than to break bonds and regenerate the hydroxide solution. This carbon-free energy would be best used to offset fossil fuel energy sources before operating DAC systems. Due to the high-energy use and uncertainties in the DAC system design, the costs for removing a tonne of CO_2 from the atmosphere is currently prohibitively expensive.

Terrestrial Bioenergy with Carbon Capture and Storage (BECCS)

Terrestrial Bioenergy with Carbon Capture and Storage (BEECS) is considered a demonstrated CDR option. The BECCS process, like afforestation and reforestation, takes advantage of the CO_2 removal abilities of photosynthesis through the growth of terrestrial biomass. Current biomass resources include forestry, dedicated energy crops, and agriculture and municipal wastes (Bauen et al., 2009). This biomass is then transformed into an energy product. Biofuels and biomass-generated electricity are energy options provided by BECCS. At the time of energy generation, CO_2 is captured and subsequently concentrated and stored to potentially produce negative emissions. Currently, primary energy from biomass is 10% of worldwide primary energy production. The International Energy Agency projects the electricity generation from bioenergy to grow to between 200 and 500 EJ/yr by 2050 while considering sustainability constraints (Bauen et al., 2009).

BECCS is appealing as a CDR option because a byproduct is consumable energy. While next generation bioenergy promises to increase energy content of biomass, the current biomass options; maize, sugarcane, woody biomass, and wastes provide flexibility of inputs to the BECCS systems. Even with this flexibility, large amounts of land are required to create the necessary biomass to have a measurable CO_2 reduction effect on the atmosphere. This large land requirement will compete with agriculture, urban growth, and other CDR options like Afforestation and Reforestation. The CO_2 removal potential of BECCS is determined by many factors such as the biomass used, the feedstocks for biomass production, where it was collected, transportation distance, and the methods of converting the biomass into an energy product. These variables may cause BECCS to become carbon positive instead of carbon negative as many of the integrated assessment models assume when using BECCS in their climate target feasibility models.

Aquatic Bioenergy with Carbon Capture and Storage (Aquatic BECCS)

Aquatic Bioenergy with Carbon Capture and Storage (BECCS) is a speculative CDR option that absorbs CO_2 via plant growth in the ocean and then uses the harvested aquatic biomass to generate energy with the capture and subsequent storage of CO_2 (N'yeurt et al., 2012). Although a variety of aquatic species might be suitable as a feedstock for Aquatic BECCS, much of the literature addresses aquatic macroalgae. In this context, aquatic macroalgae refer to a variety of kelps and seaweeds. Ideally, the expansion of such kelp and seaweed ecosystems for Aquatic BECCS would be managed in ways that promote biodiversity, increase primary productivity, as well as, sequester CO_2 from oceans (Nellemann et al., 2009; N'yeurt et al., 2012). Once seaweed has grown, it can be harvested and processed through a biodigester to generate bioenergy. The resulting CO_2 can be captured and stored to affect a net removal of carbon from the atmosphere (N'yeurt et al., 2012).

Oceans occupy over 70% of the earth's surface area and are a substantial natural carbon sink. CO_2 is taken from the atmosphere both through diffusion and dissolution in ocean water and through photosynthesis by ocean organisms (Raven & Falkowski, 1999). Currently, macroalgae occupy approximately 2% of the ocean surface (Duarte et al., 2005). That area has the potential to be expanded and used for seaweed production and harvesting to implement Aquatic BECCS (N'yeurt et al., 2012).

Aquatic BECCS directly relates to some of the other CDR options. Aquatic BECCS is very similar to Terrestrial BECCS with some minor differences. For example, as the name suggests Aquatic BECCS utilizes plant growth in water compared to land-based Terrestrial BECCS. Additionally, the process of generating bioenergy is typically different. Aquatic BECCS mostly relies on anaerobic digestion whereas Terrestrial BECCS uses a variety of approach i.e., direct fired boilers, combined cycle gasification power plants, or anaerobic digestion (Bauen et al., 2009). Lastly, although Aquatic BECCS does not face the major challenge of land use competition, Aquatic BECCS will still face competition with external industries as well as competition with ocean fertilization and the associated impact of implementation.

Ocean Storage

Ocean storage is a speculative CO_2 storage option in which CO_2 is stored in the ocean. It can be naturally removed from the atmosphere through ocean-atmospheric gas exchange. This process removes large quantities of CO_2 from the atmosphere and stores the gas within the shallow waters of the sunlit zone. This natural process, however, increases the acidity level of the water, which can affect oceanic organisms. Ocean storage, through anthropogenic means, is a form of storage where compressed CO_2 in the form of liquid, gas, or solid CO_2 is pumped into mid-level ocean depths. Due to the uncertainty with regards to the effects on ocean ecosystems, this method has not been deployed widely, nor are there many known pilot programs. In this process, CO_2 is pooled in one area and slowly releases back to the atmosphere over a period of hundreds to thousands of years. This classifies it as a long-term form of carbon storage (Sheps et al., 2009).

Ocean Fertilization

Ocean fertilization is a speculative CDR option that purposefully introduces specific nutrients into the ocean to stimulate growth of marine microscopic organisms (phytoplankton), thus removing CO_2 from the atmosphere via photosynthesis by ocean organisms (NRC, 2015; Williamson et al., 2012). Three nutrients that are typically thought of as the limiting nutrients for phytoplankton growth: iron, nitrogen, and phosphorous (Williamson et al., 2012). Ocean fertilization has been implemented in areas of the ocean called desolate zones, also known as high nutrient, low chlorophyll (HNLC) zones which lack a critical nutrient, therefore prohibiting phytoplankton or other aquatic life from growing (NASA, 2017b; Williamson et al., 2012).

Oceans, as a natural sink, allow for CO_2 to be taken from the atmosphere and stored in the ocean both through diffusion and dissolution in ocean water and through photosynthesis by ocean organisms (Raven & Falkowski, 1999). The magnitude of the net ocean sink is approximately 5.9 $GtCO_2$/yr (IPCC, 2013). Considering oceans occupy over 70% of the earth's surface area (Raven & Falkowski, 1999), a CDR approach that utilizes such a large percentage of the earth's surface sounds promising. However, the introduction of these nutrients inevitably changes the surrounding ecosystem, a major concern limiting ocean fertilization's geographic application (Bertram, 2008; Denman, 2008; NRC, 2015; Powell, 2008b).

Compared to some of the other CDR options, ocean fertilization is a fairly unique proposed CDR approach. Although ocean fertilization can relate to Aquatic BECCS through the use of simulation of aquatic growth, ocean fertilization does not parallel the majority of the other CDR options in regards to sequestration and storage process of CO_2. Additionally, compared to the other approaches, ocean fertilization has major ecosystem impacts that could severally inhibit the potential implementation of this approach.

Carbon Utilization

Carbon utilization is the notion that captured CO_2 from BECCS, DAC or other means can be used in ways beyond basic geologic storage. It is the view that captured CO_2 provides value beyond the positive removal impact to the climate. Carbon utilization provides a market for CO_2 that is sequestered. One of the main arguments against negative emission options is the cost of such endeavors. If CO_2 can be used for commercial purposes, then it can offset costs of CDR options that are used to capture it and help kick-start carbon removal activities. CO_2 can be used in the soda industry, making chemicals, cement, plastics, refrigerants, among other products.

Of all the possible products, this report chose enhanced oil recovery (EOR) to focus upon. The rationale for this is that EOR is an established option with decades of use in the oil production industry. EOR is the process in which captured CO_2 is injected into oil wells which are nearing the end of their productive lives. This injection of CO_2 increases the recoverable CO_2 as it pushes crude oil out of the pores of the sediment. EOR accounts for 6% the crude oil produced in the US (Kuuskraa et al., 2013). One of the biggest factors that make EOR appealing to CDR is that the oil wells act as a storage method. The CO_2 which stays in the wells remains there and the CO_2 which comes up with the recovered oil is injected again. While producing a source of revenue for CO_2 capture activities, EOR also uses infrastructure and knowledge of oil wells that already exist which significantly reduce the costs associated with EOR injection activities. In 2010, 50 $MtCO_2$ were injected into oil wells (Benson et al., 2013). To have a measurable impact on the atmosphere, gigatonnes of CO_2 would need to be injected and the environmental consequences of such large-scale injection are unknown.

Report Format

This report is organized into thirteen chapters. The current chapter introduces CDR and provides an overview of each CDR and storage approach included in this report. Chapter 2 explains the methodology of this study, including underlying assumptions and the statistical analysis used. Chapters 3-10 each discuss a separate CDR option. Chapters 11-13 discuss CO_2 storage options. All chapters on CDR options are organized in an identical manner, with sections that address the sequestration process, CDR potential, economic analysis, geographic restrictions, policy implications, a discussion of benefits, challenges, and tradeoffs, and suggestions for further research.

Chapter 2:

Methodology

Methodology

Process and Assumptions

This study is a comprehensive literature review of estimates of carbon dioxide removal (CDR) potential and the cost of said removal for eight CDR and two storage options. The National Research Council report "Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration" (NRC, 2015) and the IPCC's Fifth Assessment Report (IPCC, 2014) provided the starting point for this study, with subsequent queries of Web of Science, Scopus, and Google Scholar broadening the scope of literature reviewed. The following procedures were conducted on all the ten options.

Literature Review: A literature review was conducted for each option starting with the NRC and IPCC reports and followed references forward and backward to identify related studies. Subsequent queries were made using Web of Science, Scopus, and Google Scholar. Each article was analyzed specifically for CDR potential estimates as well as for cost figures of the corresponding option. Additional information was gathered regarding the current state of an option, variations in implementation, barriers to scaling, interactions between CDR options, and policy implications.

Data Extraction: Any articles that indicated CDR/storage potential or cost figures, whether from empirical research, modeling, or meta-analysis, were extracted and included in our database in their original units. These figures were further analyzed to determine the original source of estimates, if necessary. Duplicate figures from the same research study were removed. If an article presented multiple estimates, a low, medium, and high figure were extracted from the article. Estimates based on different scenarios were also extracted. Accompanying any CDR/storage potential or cost estimates, key assumptions from the article were noted in our database including the following: year the estimate was made, year(s) the estimate applies, the region of implementation, and the year cost estimates were reported in, as well as, any other key assumptions.

Data Conversion: Based on the original units, each article's CDR/storage estimates were converted into $GtCO_2e/yr$ and each article's cost estimates were converted into 2015 USD/tCO_2e.

Chapter 2: Methodology

Assumptions:

- All costs, except those projected into the future, were normalized to 2015 USD based on the US Consumer Price Index. Conversion from foreign currency was based on OANDA averages for the year of the study. The normalization process was based on the year in which the cost figures were presented. If the cost figures were not specified in a given year, the year the article was published was used as a proxy.
- Any cost figures originally presented in Euros were converted to USD based on the rate presented in the article. If an article did not present a Euro to USD conversion, a proxy was used from an article that presented a Euro to USD conversion for the same year. The following is a list of Euro to USD conversions used within this report: Can Ozcan, et. al. 2014 (1 USD: 0.77 EURO); Kohler, 2010 (1 USD: 0.755 EURO).
- Carbon dioxide (CO_2) mass units, unless specified, were converted and reported in metric tonnes (t) and metric gigatonnes (Gt).
- Estimates of CDR/storage potential were standardized to Gt of CO_2 equivalent (CO_2e) to include reports that factored methane, nitrous oxide, and VOCs into their estimates.
- Estimates reported at a daily rate were multiplied by 365.25 days per year and reported as a yearly estimate.
- Multi-year estimates were standardized to an annual basis through a straight-line allocation method.
- Per hectare, or other area estimates, were extrapolated to a cumulative figure based on the area presented in the article. If an area was not specified in an article, an assumed area was applied in order for a cumulative figure to be presented. Refer to each chapter for the assumed area of implementation.
- Studies based on a reduced geographic region or country basis were reported with their original localized estimates instead of extrapolating to a global implementation level. It was determined that global extrapolation would oversimplify underlying idiosyncratic differences between regions, which could lead to drastic over- or under-reporting of actual sequestration potential.

Data Analysis: After all data was converted to standardized CDR/storage and cost units, the data was further analyzed based on the amount and quality of observations. If the literature review resulted in greater than or equal to 9 observations and the estimates were deemed relatively comparable, descriptive statistics was used. A quartile analysis was conducted to determine the minimum, 1st quartile, 2nd quartile (median), 3rd quartile, and maximum. Using the minimum and maximum figures, an overall range was calculated. The 1st through 3rd quartile represent the middle 50% of estimates. The 2nd quartile represents the median. This analysis was conducted to determine the distribution of estimates. Note this analysis is solely for descriptive purposes and the estimates generated from this analysis are not inferential statistics. They are summary statistics chosen to provide a more detailed view of the data than could be demonstrated through a simple range. Before analyzing the box-and-whisker plots in each chapter, refer to the previous graph within the chapter to determine the number of estimates (data points) used in the creation of this quartile analysis. If the literature review did not result in greater than or equal to 9 observations or the estimates were not deemed relatively comparable, a quartile analysis was excluded from the process and an alternative analysis was conducted. This analysis consisted of further research into the assumptions made by the articles and the corresponding estimates. Based on the discretion of the research team, an article and a related estimate were chosen to represent that CDR option when comparing it to the other options. A justification for why a specific estimate was used is provided in each chapter if this alternative process occurred.

Review: Academic and professional experts on each option were consulted through conferences and direct communication for a review of initial results and recommendations regarding additional data and considerations that should be included in the final analysis. The feedback from experts was assessed and incorporated into our database.

Chapter Reporting: Finally, graphs and their corresponding chapters were created to analyze each CDR/storage option as well as to compare standardized CDR/storage potential and cost estimates across the ten options. Each chapter follows a standardized format with subsections on the sequestration and storage process, the CDR removal potential, financial cost estimates, geographic restrictions, policy implications, and the benefits and challenges of the option, and recommendations for future research.

Reporting Format

This literature review provides estimates for each option in four graphs. However, as noted above, either the second or fourth graph may be excluded from the chapter.

The first graph in each chapter reports estimates of CDR/storage potential from the reviewed studies. On the y-axis is the list of the sources with any pertinent assumptions listed below following an asterisk. On the x-axis, the amount of CDR/storage potential is reported in $GtCO_2e$.

The second graph, a box-and-whisker plot, summarizes the CDR estimates from the first graph through the use of descriptive statistics. A quartile analysis provides the minimum, 1st quartile, 2nd quartile (median), 3rd quartile, and maximum. It is important to note that quartile divisions are not confidence intervals. The following is an explanation of the box-and-whisker plot: the minimum estimate is represented by the end of the whisker at the bottom of the plot; the 1st quartile is represented by the bottom line of the two adjacent rectangles; the 2nd quartile, median, is represented by the middle line of the two adjacent rectangles; the 3rd quartile is represented by the top line of the two adjacent rectangles; the maximum estimate is represented by the end of the whisker at the top of the plot.

Cost estimates for all studies reviewed are reported in the third graph. On the y-axis is the list of the sources with any pertinent assumptions listed below following an asterisk. On the x-axis, the estimated cost is reported in 2015 USD/tCO_2e.

The fourth graph, similar to the 2nd graph, is a box-and-whisker plot that summarizes the cost estimates from the third graph through the use of descriptive statistics. A quartile analysis was conducted to obtain the minimum, 1st quartile, 2nd quartile (median), 3rd quartile, and maximum. It is important to note that quartile divisions are not confidence intervals. The following is an explanation of the box-and-whisker plot: the minimum estimate is represented by the end of the whisker at the bottom of the plot; the 1st quartile is represented by the bottom line of the two adjacent rectangles; the 2nd quartile, median, is represented by the middle line of the two adjacent rectangles; the 3rd quartile is represented by the top line of the two adjacent rectangles; the maximum estimate is represented by the end of the whisker at the top of the plot.

Chapter 3:

Afforestation and Reforestation

Afforestation and Reforestation

Introduction

Key Findings

- *Afforestation/reforestation is an established CDR option due to its current implementation and extensive empirical research.*
- *Afforestation/reforestation has the potential to capture and store 1.1 $GtCO_2e$/year at an approximate cost of $30/$tCO_2e$.*
- *However, when all current literature is considered, the estimates range between 0.02 – 13.8 $GtCO_2e$/year at a cost between $2 - $100/$tCO_2e$.*

Afforestation and Reforestation (AR) are commonly referenced land management methodologies that sequester carbon dioxide (CO2) from the atmosphere via biomass growth in trees. Afforestation is the process of foresting land that never contained forests or restoring land that has been deforested over 50 years ago to a forested state. Reforestation is the process of restoring land to a forested state that has been deforested less than 50 years ago (NRC, 2015). Although there is a minimal difference between these two carbon dioxide removal (CDR) options, this report will evaluate both collectively.

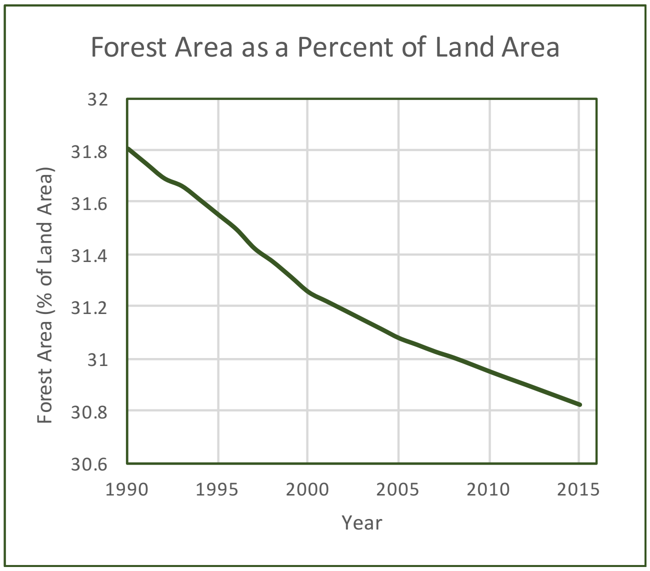

Figure 3-1: Graph of the percent of forest area to land area on earth (World Bank, 2016).

Over the past 25 years, world forest area has been steadily declining due to causes that include population growth and density; increased agricultural demand; market, policy, and institutional failures; trade; and cultural factors (Contreras-Hermosilla, 2000; MacDicken et al., 2016). See Figure 3-1 for a graphical depiction of forest area as a percent of land area. In 2013, forest land occupied 30.9% of the world's land area, compared to 37.7% of world land area devoted to agricultural purposes (World Bank, 2016). The total forest area declined from 4,128 million hectares in 1990 to 3,999 million hectares in 2015 (MacDicken et al., 2016). While natural forest areas continue to decline, planted forest area is increasing, having increased by over 110 million hectares between 1990 and 2015 (MacDicken et al., 2016). Considering forestry and other land use contributed approximately 12% of the world's GHG emissions from 2000 to 2009 (Smith et al., 2014), monitoring and preserving currently forested land, as well as pursuing afforestation and reforestation, are critical factors in climate change mitigation and intervention strategies. Forests, although thought of as a natural sink for CO_2, can easily become a source of CO_2 through deforestation (NRC, 2015). Although the amount of GHG emissions from deforestation is decreasing, emissions in 2010 directly related to deforestation were approximately 3.7 $GtCO_2e$ (FAO, 2014). Reducing this source of CO_2 emissions while creating additional CO_2 sinks will play a critical role in reducing global net GHG emissions.

It is important to note that this chapter does not discuss preexisting forests and their annual sequestration rates or carbon stocks nor does it discuss the CO_2 that is released/produced due to deforestation. Instead, this chapter discusses the sequestration and storage potential of converting non-forested land into forested land and maintain it over a long-time horizon through defined management techniques.

The Afforestation and Reforestation (AR) Process

Afforestation/reforestation is considered an established CDR option. Trees have been removing carbon from the atmosphere for millennia, and substantial empirical research has established methods to document potential contributions of afforestation and reforestation to carbon sequestration (Garcia-Oliva & Masera, 2004; Lal, 2006; Richards & Stokes, 2004). Afforestation/reforestation is a land management CDR approach that combines the sequestration/capture and the storage/disposal of CO_2 in a single process in the same geographic location.

Afforestation/reforestation involves a form of land use change in which an area previously used for farmland, pastures, industrial production or another use is transitioned to forested land. The transition can occur passively through secondary succession or through an active restoration process such as the planting of native species or the establishment of a managed tree plantation (Rey Benayas, 2005). More reforestation on abandoned land has occurred through passive restoration, but active restoration is needed where drought conditions exist, when weeds outcompete native plants, and where seed dispersal can no longer occur (Rey Benayas, 2005).

While some studies indicate that the initial transition to afforestation/reforestation can result in short-term CO_2 net emissions (Paul et al., 2002), managed forests eventually provide large net CO_2 removal from the atmosphere since carbon is stored indefinitely within the forest biomass. Carbon uptake rates vary by species, but tend toward an increasing uptake during the first few decades of a tree's life, followed by a gradual decline. For example, the loblolly pine has a rapid carbon uptake in its early years, which peaks after two decades and then approaches zero by year 70 (Stavins & Richards, 2005). In contrast, the ponderosa pine exhibits a steady increase in its carbon uptake rate until it peaks at about 65 years after planting (Stavins & Richards, 2005). For all tree species, later years are marked by lower rates of tree carbon gain since more energy is spent on sapwood maintenance respiration (Turner et al., 1995).

Afforestation/reforestation relies on the natural sequestration of CO_2 in tree biomass for prolonged periods. Through the photosynthesis process, trees take in CO_2 from the atmosphere, store the carbon within their trunk, branches, and roots (above-ground and below-ground woody biomass) and then release oxygen back into the atmosphere through respiration (Vashum & Jayakumar, 2012). The carbon is stored for an extended period within the woody biomass of the tree or tree-derived products. The rate of sequestration is highly dependent upon the ambient CO_2 concentration, forest site history, the age and species of the trees within the forest, temperature, geology, and precipitation (Reyes Benayas, 2005; Turner et al., 1995). For example, forests in the Southeast region of the United States recover faster than the Douglas-fir forests of the Pacific Northwest based on tree species (Turner et al., 1995). Likewise, the cold, dry climate of the Rocky Mountains cause regional forests to have a much slower rate of carbon uptake than the warm Southeast and South Central regions and the rainy western Pacific Northwest region of the United States (Turner et al., 1995).

Forests can be a source of CO_2 not only through deforestation for timber harvesting but also through the natural process of biomass decomposition or forest fires (Lal, 2005). In this way, land management is critical for preventing forests from becoming a source of CO_2 emissions and to increase the forested areas that can serve as a carbon sink. As a CDR option, afforestation and reforestation can remove CO_2 from the atmosphere at varying rates at multi-decade or longer time scales depending on management practices used and risks due to fire, disease, or reverting to another land use.

The Afforestation and Reforestation Process

As envisioned by (Nepstad et al., 1996), the overall process based on a managed forest plantation would consist of the following steps:

1. **Site selection:** the land to be used for afforestation or reforestation is chosen based on land use history, existing ecosystem species, and native species.
2. **Seedling establishment**: seeds or seedlings are planted on the land intended for afforestation or reforestation. Choice of seed stock can be based on growth rate or status as a native species.
3. **Sapling survival and growth**: germinated seeds and seedlings grow and begin to take up CO_2 from the atmosphere. However, a percentage of the plants do not survive, due to biotic and abiotic factors.
4. **Plantation management**: the forest is managed with occasional thinning and fire suppression measures to ensure healthy growth and long-term storage of carbon as above- and below-ground biomass.
5. **CO_2 uptake through photosynthesis**: trees along with the understory shrubs and plants in a managed forest remove CO_2 from the atmosphere for use in photosynthesis, which produces oxygen and some CO_2 as a byproduct of creating and expending energy.

Carbon Dioxide Removal Potential of Afforestation and Reforestation

The CDR potential of afforestation/reforestation is highly dependent on the approach used, specifically the rate of afforestation/reforestation; planting configuration and management techniques including the species planted and its age; the geographic location and its characteristics such as temperature, precipitation, geology, site history, and CO_2 concentration (NRC, 2015). Based on the literature review conducted within this study, most recent estimates primarily focus on stocks and flows of CO_2 rather than the CO_2 sequestration potential of afforestation/reforestation. After accounting for the previously mentioned variations, it is estimated that afforestation/reforestation has the potential to sequester and store between 0.01 and 13.8 $GtCO_2e$/year. The CDR potential of afforestation/reforestation is listed by source in Figure 3-2.

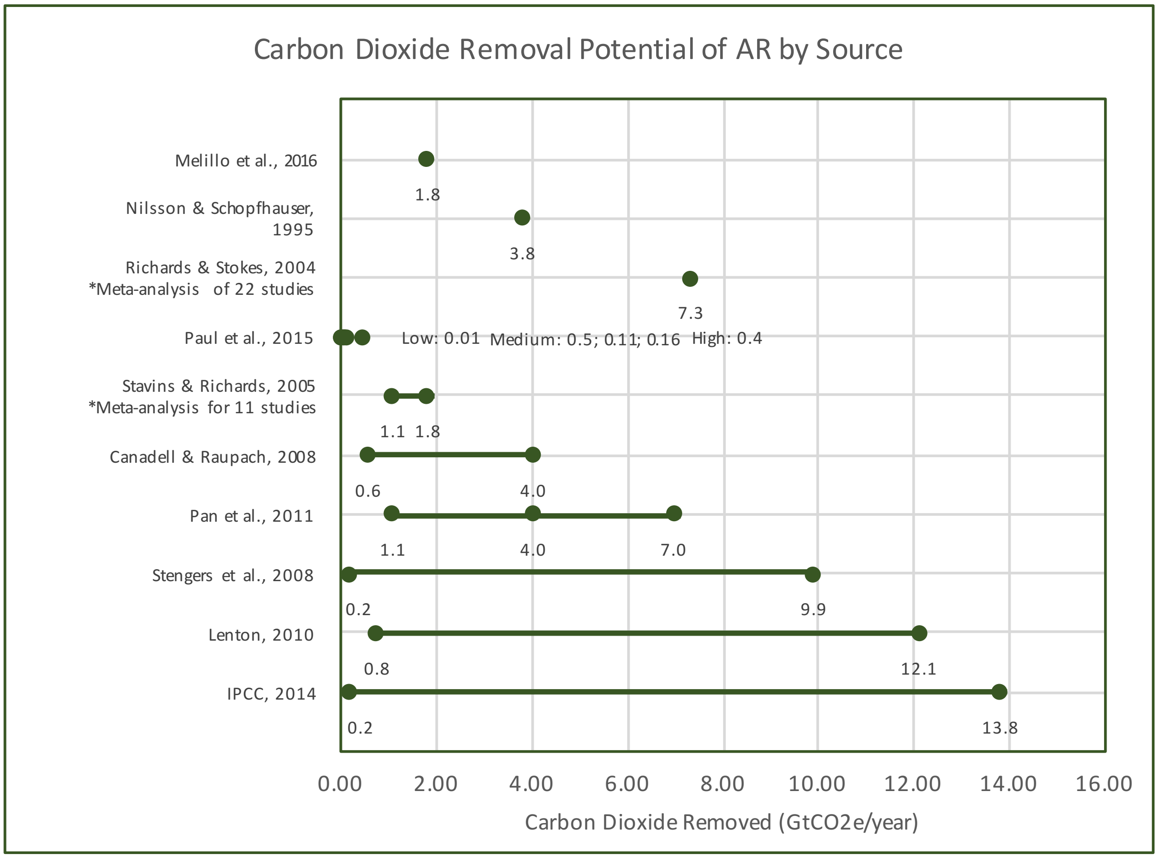

Figure 3-2: Graph of Carbon Dioxide Removal Potential in Gt of carbon dioxide equivalency per year of Afforestation/Reforestation. *Key assumptions made by the original author(s) or this research team are listed below the source.

The variation in the amount of CDR potential listed by different sources, 0.01 - 13.8 $GtCO_2e$/year, is primarily attributed to the major assumptions used in each study. One of the key assumptions that produced variation in the data was the quantity of land area in which afforestation/reforestation would be implemented. Some of the studies specified an assumed geographic area, other studies assumed a less specific area, and two others stated an assumed area based on hectares. For example, Strengers (2008), assumed 100% of the world's abandoned agricultural land would be afforested/reforested with plantations involving the conversion of approximately 2-18 million hectares (Mha)/year between 2000 and 2100 and sequestering an average of 2.2 and 3.4 tC/ha in 2010 and

2100, respectively. Alternatively, Nilsson & Schopfhauser (1995) provided world estimates assuming an area of 345 million hectares (Mha) while Lenton (2010) provided world estimates assuming an area of 246 Mha. Because this data was not originally presented on a per hectare basis we did not extrapolate the data to a per hectare basis and then back to an aggregate figure based on a reasonable area, a process that was conducted on some studies in the other CDR approaches.

A second key assumption that produced variation in the data was related to the type of species planted. Based on the geographic area of afforestation/reforestation implementation, different species of trees will need to be planted. For example, the results from Paul (2015), are based in Australia on assumed areas of 107 Mha using five different types of plantings. These five types of planting included three monocultures of 1) eucalyptus polybractea, 2) E. lox-ophleba ssp. lissophloia and 3) other key species of eucalyptus/mallee; one mixed temperate species planting; and one planting of a mixed tropical species (Paul et al., 2015). The type of trees that are used will directly affect the carbon fixation rate that is assumed within studies. For example, Nilsson & Schopfhauser's (1995) study assumed the following, "0.3 tons C/m^3 stemwood for Canada, the U.S.A., Europe, the former Soviet Union, China, temperate Asia, temperate South Africa and temperate South America… 0.4 tons C/m^3 stemwood for New Zealand, Australia, and the Tropics". Whereas, Lenton (2010) assumed an average carbon sequestration and storage rate of 0.8 - 1.6 MgC/ha/year. Other studies assumed different carbon fixation/sequestration and storage rates.

There are many variations within the studies that can drastically impact the potential amount of CDR potential. Two of the studies included in this report are based on meta-analyses. Richards & Stokes (2004) is a meta-analysis based on 22 global and U.S. studies. These studies were standardized across different measurement methods used for forest plantations, forest management, and agroforestry. Alternatively, Stavins & Richards' (2005) meta-analysis was based on 11 U.S. forest carbon sequestration studies. The in-depth analysis and standardization process that took place in these meta-analyses lends credibility to these U.S. based estimates as well as indicates the volume of research that has been conducted on afforestation/reforestation in the U.S.

The previously mentioned assumptions contribute to the variation among the results presented in Figure 3-2. Because there is substantial variation between the estimates and in the range of estimates from the studies, further analysis was conducted. Using a quartile analysis, 50% of the data sources suggest that afforestation/reforestation could sequester and store between 0.2 - 4 $GtCO_2e$/year with a median figure of 1.1 $GtCO_2e$/year. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 3-3.

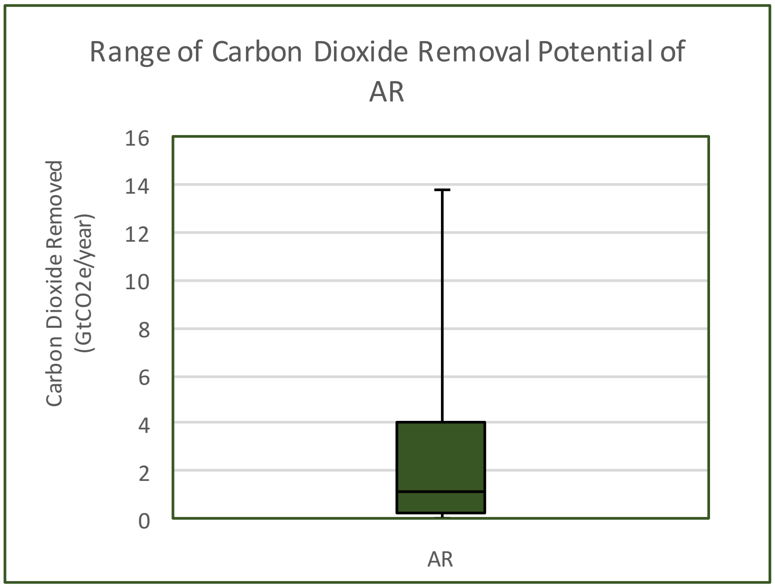

Figure 3-3: Graph of range of carbon dioxide removal potential in Gt of carbon dioxide equivalency per year of Afforestation/Reforestation. Min: 0.01; 1st: 0.22; Median: 1.10; 3rd: 4.03; Max: 13.80 $GtCO_2e$/year.

Economic Analysis of Afforestation and Reforestation

Since afforestation/reforestation is an established land management option that does not require significant economically-restrictive resources and inputs, the costs of implementing this CDR approach is typically lower compared to other CDR options which are energy intensive. Depending on geographic location, opportunity cost of land, and monitoring and oversight, afforestation/reforestation costs range from approximately \$2/tCO_2e to \$100/tCO_2e. Estimated financial costs of afforestation/reforestation are listed by source in Figure 3-4.

As seen in Figure 3-4, there are five recent sources that provided economic cost data. However, as mentioned above, Richards & Stokes (2004), and Stavins & Richards (2005) are meta-analyses that analyzed 22 and 11 studies, respectively. Although two of the five estimates, Richards & Stokes (2004) and Stavins & Richards (2005) were adjusted and levelized for differences, there still is substantial variation among the estimates. This variation can be attributed to several factors including different discount rates and the inclusion and exclusion of different direct and indirect costs such as land costs and opportunity costs.

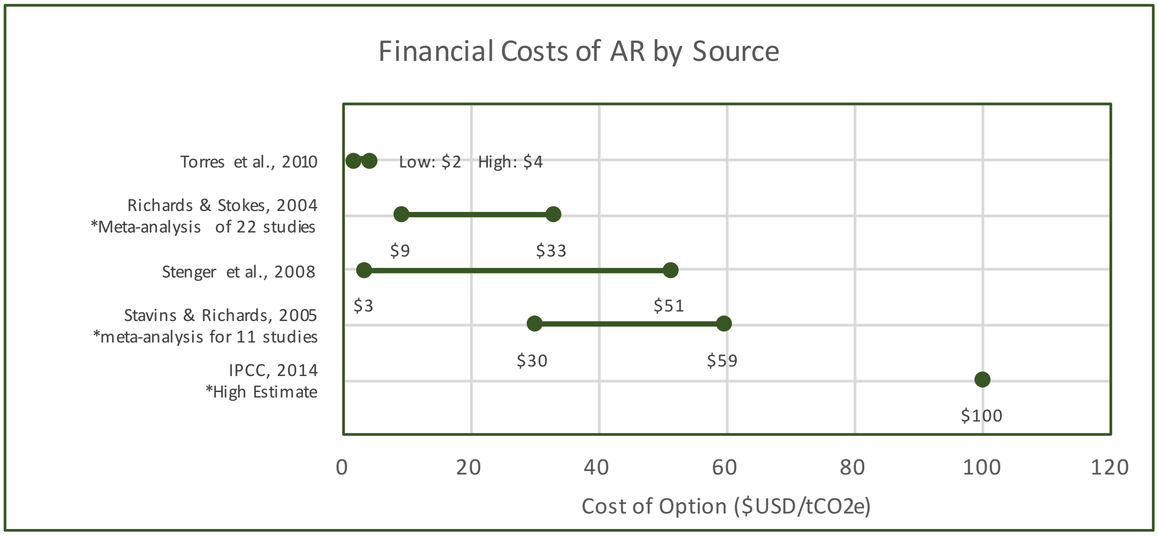

Figure 3-4: Graph of financial costs of Afforestation/Reforestation in 2015 US Dollars per tonne of carbon dioxide equivalency. *Key assumptions made by the original author (s) or this research team are listed below the source.

Although many of the studies mentioned some of the cost categories, most studies solely provided aggregate cost figures or only included some of the cost figures while excluding others. For example, Strengers (2008) only accounted for land and establishment costs and excluded operation and maintenance, monitoring, and certification costs. Torres (2010) included only direct landowner costs. An explicit, distinguishable difference between the studies was the discount rate. Discount rates can vary between studies because it is a subjective opinion how much money earned or spent in the future is worth today. A 10% discount rate was used within Torres (2010), a 4% discount rate was used on land costs in Strengers (2008), and a 5% discount rate was used in Stavins and Richards (2005).

Although not explicitly analyzed within the studies, it can be assumed that the geographic region of implementation can have an effect on the cost of afforestation/reforestation. The geographic region can impact both direct and indirect costs such as land, material, labor, management and opportunity costs, as seen in various markets around the world. To potentially account for this, Strengers (2008) decided to use a world average establishment cost figure of approximately \$435/ha, which accounts for the cost of "land clearing, land preparation, plant material, planting and replanting, fences and administrative and technical assistance" (Strengers et al., 2008).

Again, as seen in Figure 3-4, there is substantial variation among the estimates; therefore, further analysis was conducted. Based on a quartile analysis from all sources, 50% of the data suggests afforestation/reforestation costs between \$4 - \$51/tCO_2e with a median cost of \$30/tCO_2e. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 3-5.

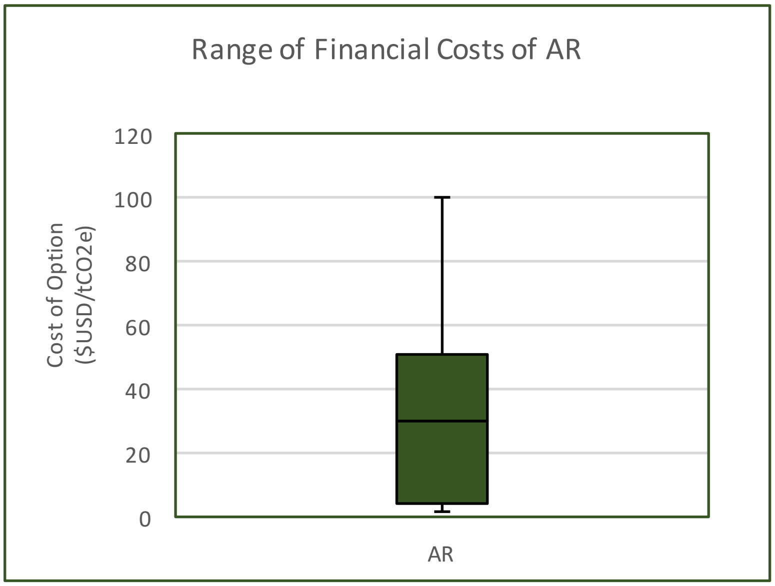

Figure 3-5: Graph of range of financial costs of afforestation/reforestation in 2015 US Dollars per tonne of carbon dioxide equivalency. Min: 2; 1st: 4; Median: 30; 3rd: 51; Max: 100 \$USD/tCO_2e.

Geographic Restrictions

Theoretically, afforestation/reforestation could be implemented on any land that is capable of supporting tree growth and is not currently forested. This land includes the terrestrial portion of the earth’s surface that is not above the treeline and does not have slopes too steep for tree establishment. In 2013, forest land occupied 30.9% of the world’s land area, compared to 37.7% of world land area devoted for agricultural purposes (World Bank, 2016). See Figure 3-6 for a map depicting country based forest area as a percent of land area in 2015.

Increasing forest area through afforestation/reforestation implies a tradeoff with other potential land uses. Some of those uses that are in direct competition with afforestation/reforestation could include agriculture, urban development, as well as the other CDR options such as soil carbon sequestration and terrestrial BECCS. Given the significant land competition that exists today, it will be imperative for governments to analyze the impacts associated with afforestation/reforestation compared to other land uses. For example, if land were to be converted from agriculture, it will be important to assess the impacts on biodiversity, community livelihoods, and food security within the region (Zomer et al., 2008)

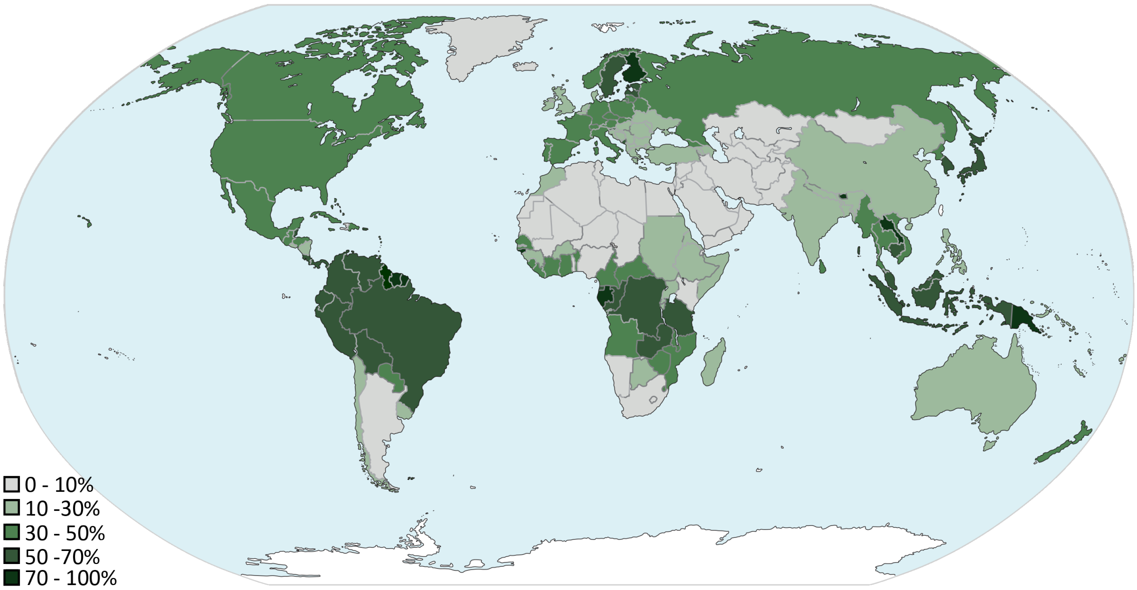

Figure 3-6: 2015 world map of forest area as a percent of land area. Image adapted from FAO, 2016.

Policy Implications

Global policies implemented over the past decades have sought to protect forest areas from deforestation and expand total forested land within their borders. While some countries like Bhutan, Gambia, and Vietnam have experienced success in afforestation/reforestation (Chazdon, 2008), the overall pace of deforestation has also slowed. Brazil decreased deforestation rates by 59% over three years leading up to 2008, in part through the Amazon Protected Areas Program, which provides land protection and encourages registration of protected and sustainable use lands (Tollefson, 2008). Developing countries that strive to reverse the effects of deforestation can receive support from the Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) program. Established by the United Nations, REDD+ provides support not only to countries that strive to reduce emissions from deforestation but also those that are enhancing forest carbon stocks (Fischer et al., 2016)

To promote greater carbon sequestration through afforestation/reforestation, policies must be enacted to limit the competition between forests and farmland, especially when food commodity prices rise (Tollefson, 2008). Going beyond a limitation on forces that could trigger deforestation, countries should account for the ecosystem services offered by forests. The European Union has created a model for this practice in the spatial assessment of ecosystem services commissioned by the EU Biodiversity Strategy (Maes et al., 2012). Another area for consideration is the role of selective harvesting, allowing some economic benefits from forest management while promoting an overall net increase in carbon sequestered through management techniques that mimic natural forests (Lal, 2005). Newell & Stavins (2000) found that afforestation/reforestation could be implemented at higher implementation costs when periodical harvests were allowed. All these policies can incentivize afforestation/reforestation and protect it from reversal if conditions change.

Benefits, Challenges, and Tradeoffs

In addition to CDR, afforestation/reforestation provides ecosystem services that include enhanced biodiversity, buffering against flooding, and localized climate moderation (Chazdon, 2008). Forests provide habitat and a rich matrix for wildlife. Their root systems increase water absorption and decrease runoff during heavy rain events. Furthermore, forested areas decrease the range of temperatures in surrounding areas. However, benefits of afforestation/reforestation through CDR and ecosystem services can also become a tradeoff. Naturally reforested areas tend to contain more native species and more closely resemble the original forest area (Rey Benayas, 2005). However, managed forest plantations may provide higher carbon sequestration, resulting in the need to prioritize either CDR or biodiversity.

One of the major drawbacks of afforestation/reforestation is the challenge of ensuring the permanence of CO_2 storage. This CDR option depends on maintaining carbon stored within the woody biomass of the tree or in wood products with a long expected lifetime, so it risks becoming a future source of CO_2 . Productive use in durable goods such as furniture and houses is one option to extend the time period of CDR through afforestation/reforestation. The CO2FIX carbon sequestration model even factors in three product use scenarios at one, 15, and 30 years of additional storage (Masera et al., 2003). Zeng (2008) has also proposed that logs be harvested and then buried in trenches with anaerobic conditions that would prevent decomposition. Afforestation/reforestation can easily become a source via direct anthropogenic causes such as deforestation and forest fires or indirect human-induced behavior and natural disasters that include tree falling, invasive diseases, hurricanes, tsunamis, etc.

Further Research

Given that afforestation/reforestation is an established CDR option, a substantial amount of theoretical and empirical research has been conducted regarding the viability, economic costs, and CDR potential of afforestation/reforestation compared to some of the speculative and developing CDR approaches. Further research is still needed prior to wide-scale implementation. A focus should be placed on determining the cost of afforestation/reforestation as well as which species or mix of species would yield the highest CDR potential on a regional basis. Additionally, given the projected impacts of climate change, further research should be conducted on the likelihood of permanence which could easily be affected by natural and anthropogenic forces. Determining country- and region-specific information will be important before governments can decide whether and when to implement afforestation/reforestation rather than other GHG mitigation measures.

Conclusion

In conclusion, afforestation/reforestation is an established CDR option due to its current implementation and extensive empirical research. Afforestation/reforestation has the potential to capture and store 1.1 $GtCO_2e$/year at an approximate cost of \$30/tCO_2e. However, when all current literature is considered, the estimates range between 0.02 – 13.8 $GtCO_2e$/year at a price between \$2 - \$100/tCO_2e. Further research is necessary to determine the cost of afforestation/reforestation as well as which species or mix of species would yield the highest CDR potential based on a specific region.

Chapter 4:

Soil Carbon Sequestration

Soil Carbon Sequestration

Introduction

Key Findings

- *Soil carbon sequestration is a demonstrated CDR option due to the implementation of small-scale projects.*
- *Soils have the potential to capture and store 1.3 $GtCO_2e$/year at an approximate cost of \$8.25/tCO_2e.*
- *However, when all the literature is considered, the estimates range between 0.1 – 13 $GtCO_2e$/year at a cost between \$5.5 - \$11/tCO_2e.*

Soil carbon sequestration is a carbon dioxide removal (CDR) option that relies on intentional land management targeted at increasing the storage of carbon as soil organic matter and in labile, inorganic forms. While any type of soil can be a carbon sink, this report focuses specifically on conservation management of cropland and pastures as well as the conversion of former agricultural land to other uses with higher CDR potentials. Within the latter scenario, former agricultural land that is reforested or afforested is addressed in Chapter 3 of this report. The ability of soil to remove carbon dioxide (CO_2) from the air is dependent on natural processes that can easily be altered by changes in management practices. For instance, switching crop varieties could result in lower carbon sequestration in the soil because of new plants that do not produce as much leaf litter. Alternatively, the management choice to apply less fertilizer in a more efficient way could avoid N_2O emissions (Smith et al., 2008). Therefore, storage and cost potentials vary based on the management technique and ecological conditions in an area.

The Process of Storing Carbon in Soils

As part of the global carbon cycle, plants take in CO_2 through photosynthesis, incorporating it into plant biomass. This biomass can be harvested if it is on cropland, consumed by animals in pastures, or stored over a long time as above ground biomass. All three of these situations prevent the majority of plant carbon from entering the soil. However, below ground plant root systems account for as much as half of plant biomass, immediately predisposing that portion to remain in the soil (Magdoff & Van Es, 2000). Additionally, annual deposition of dead organic material in the leaf layer can either become part of the topsoil or cycle back to the atmosphere through decay and soil respiration. It is estimated that on average, 10% of the carbon from organic material remains for 20 years after it enters the leaf layer (Lehmann et al., 2006).

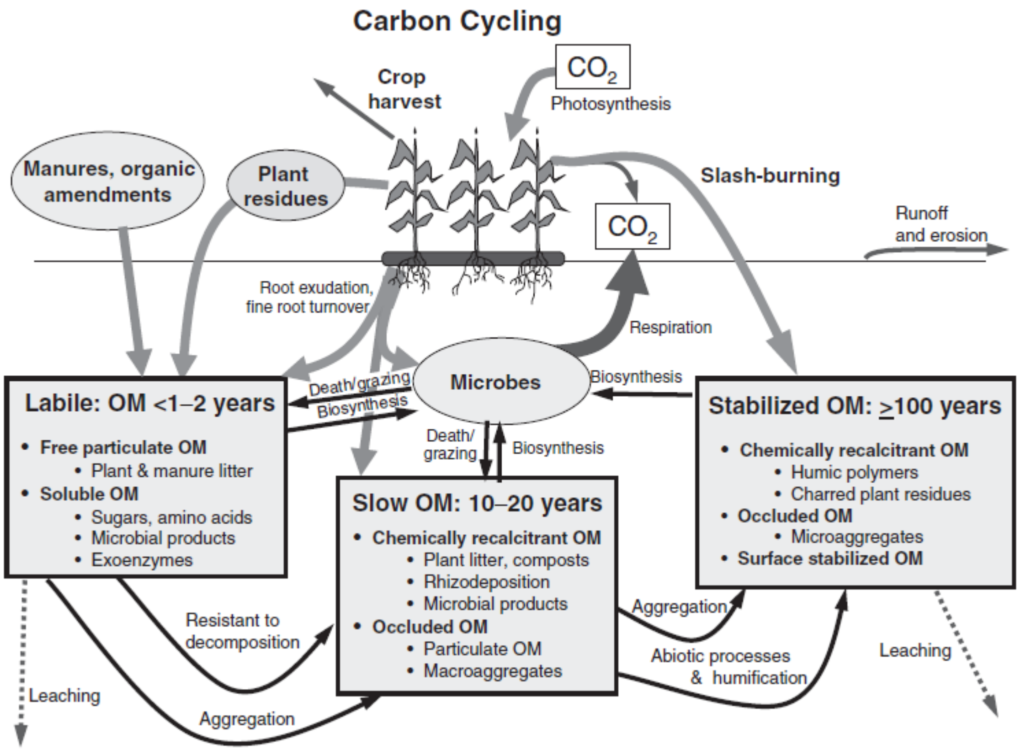

Figure 4-1: Soil Carbon Cycle. Image from Drinkwater, 2008.

Since soil carbon sequestration is based on the difference between carbon stored in soil in each year and the amount returned to the atmosphere, the actual amount of net soil carbon sequestration can be negative and can have broad fluctuations from year to year depending on management practices (Post & Kwon, 2000).

The location of carbon within the soil is a factor that determines the ease with which the carbon could return to the atmosphere. Soil carbon exists in three forms: labile organic matter, slow organic matter, and stabilized organic matter (Drinkwater, 2008). Labile organic matter normally has entered the soil through the leaf layer or the root system within the past 1-2 years and can most easily return to the atmosphere. Slow organic matter tends to have been in the ground for 10-20 years and exists lower in the soil horizon where oxygen for decomposition is less available. The slow organic matter is still available to plants and microbes for nutrients but is less likely to return to the atmosphere. Finally, stabilized organic matter such as humus has often accumulated in the soil for at least 100 years and is unlikely to return to the atmosphere without human interference (Drinkwater et. al., 2008).

Agricultural practices have traditionally tilled up the soil before the planting of new crops. This process can break up old roots and bury undesirable plant material, making it easier to plant the new crop. This practice can also be beneficial to crop yields because it loosens up the soil for the new plant’s root system to grow. However, tilling the soil exposes layers of organic material, specifically slow organic matter, that was locking in carbon and thus starting up the decaying process again.

In croplands, two practices from conservation agriculture are most likely to ensure that soil in agricultural landscapes serves as a sink rather than a source of carbon. The first, cover cropping, involves planting crops for non-economic benefits. These crops can be planted between the rows of a cash crop during the growing season or on what would otherwise be bare ground during the winter. Cover crops provide soil cover to lock in nutrients that might otherwise be eroded. They also increase the amount of carbon in soil organic matter when they are left on the field at the end of the growing season. The second conservation agriculture process is called no-till, and it involves planting directly

The Process of Storing Carbon in Soil

The overall process would consist of the following steps:

1. Plant life takes in CO_2 through photosynthesis.
2. As plant life dies or is harvested, the biomass is left on the ground to decay
    a. This biomass consists of leaf litter, above ground plant growth, and root systems
3. When oxygen is present, the biomass will decay. This decay will slow down or stop completely if the oxygen is limited. This will happen if the biomass is covered with additional plant material (i.e. leaf litter in a forest), or is already located deep in the soil (i.e. roots).
    a. Microbial activity facilitates the decaying process, and these microbes respire CO_2 back into the atmosphere.
4. With decomposition halted, the carbon in the biomass is therefore stored in the soil.

into last year’s harvest stubble without tilling the soil. This decreases soil aeration which would otherwise trigger soil microbial activity that releases CO_2 through respiration.

Carbon Dioxide Removal Potential of Soils

Soil carbon sequestration on a global scale can be divided by region, type of soil managed, and the management technique employed. Within the US, agricultural soils could potentially store 0.3-4.6 $GtCO_2e/yr$ through tillage management and cropping systems (Eagle, 2012). The practice of planting cover crops, winter crop cover, and the utilization of conservation reserve programs adds to the potential to sequestering an extra 0.014-.029 $GtCO_2e/yr$ (Eagle, 2012). Also, nutrient inputs and supplemental irrigation could potentially sequester 0.011 – 0.03 $GtCO_2e/yr$ (Eagle, 2012).

Pasture Land

Pasture lands, used for grazing cattle, sheep, and other animal herds, pose another potential opportunity for soil carbon sequestration. The lack of physical disturbance through tillage and high root density of pasture plant species make pasture land an attractive option for carbon sequestration. It is estimated that 0.03 – 0.11 GtC/yr (Eagle, 2012) can be sequestered in the soil of pasture land in the United States.

Wetlands

Beyond terrestrial land that is actively managed by humans, wetlands have received substantial attention as both potential carbon sources and sinks. An estimated 500-700 $GtCO_2e$ are stored in wetlands around the world, and the draining of these areas for agriculture or other use can rapidly release substantial quantities of greenhouse gases that had been stored for decades to centuries (Mitch & Gosselink, 2015). However, wetland restoration has the potential to return coastal and inland areas to their natural role as both regulators of the terrestrial water cycle and sinks for CO_2. Although wetlands are a CO_2 sink, they also serve as a source of methane, which is twenty-eight times more potent than CO_2 as a greenhouse gas. Nonetheless, extensive research on greenhouse gas flows in wetlands has established that these areas emit an estimated 0.448 $GtCO_2e/yr$ as methane while they sequester 1.280 $GtCO_2e/yr$ for a net average sequestration of 0.832 $GtCO_2e/yr$ (Mitsch et al., 2013).

Overall, studies have estimated global CO_2 sequestration potential while also researching options in specific regions and based on single land or land use scenarios. Combining information from studies across various scenarios, it is estimated that soil carbon sequestration has the potential to sequester and store between 0.1-13.1 $GtCO_2e$/year. Figure 4-2 shows the CDR potential of soils by source.

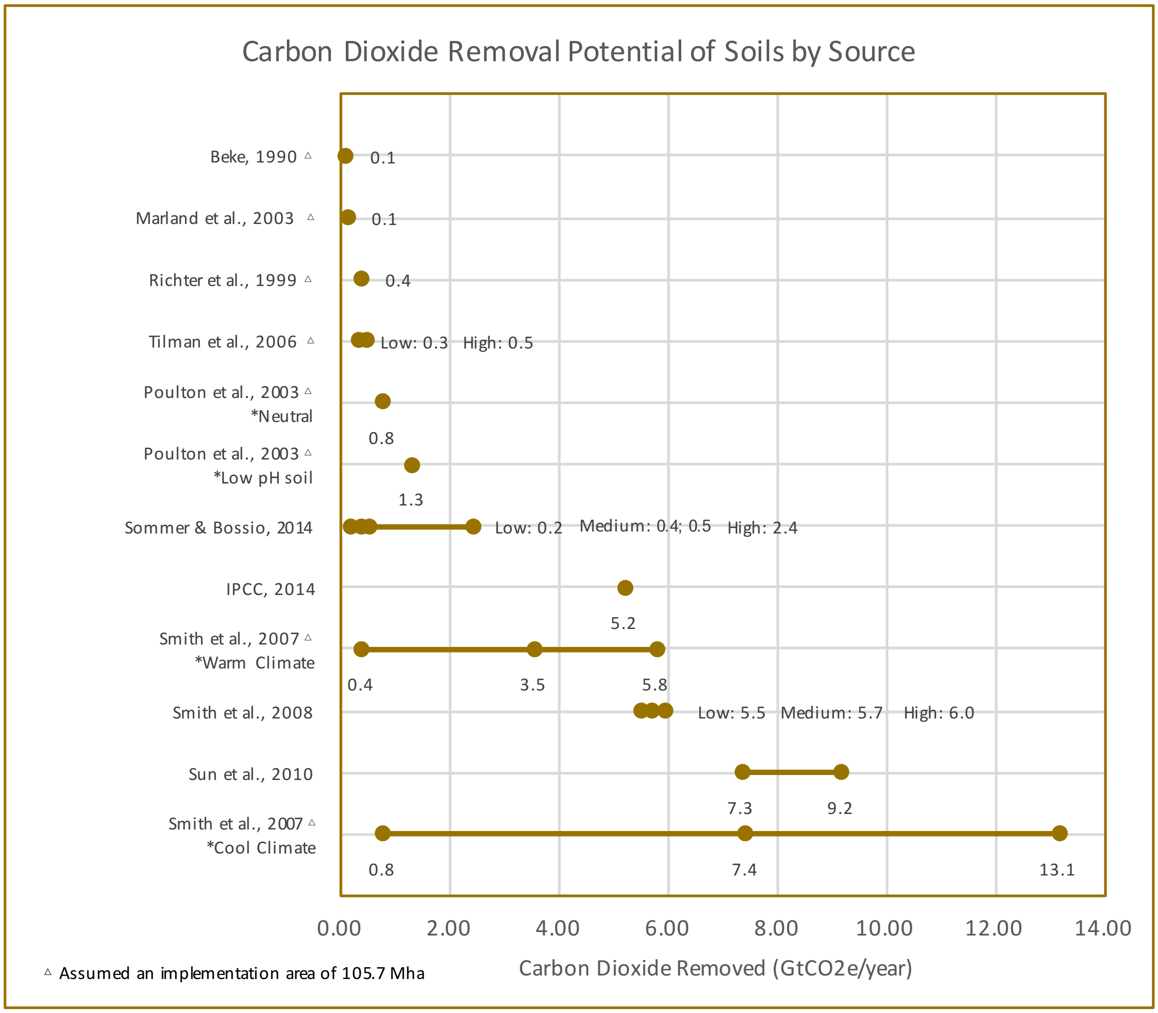

Figure 4-2: Graph of Carbon Dioxide Removal Potential in Gt of carbon dioxide equivalency per year of Soils. *Key assumptions made by the original author(a) or this research team are listed below the source.

As seen in Figure 4-2, there is substantial variation between the estimates/range of estimates from the studies, 0.1 – 13.14 $GtCO_2e$/year, therefore, further analysis was conducted. Using a quartile analysis, 50% of the data suggests that soil carbon sequestration could sequester and store between 0.39 and 5.75 $GtCO_2e$/year with a median figure of 1.31 $GtCO_2e$/year. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 4-3.

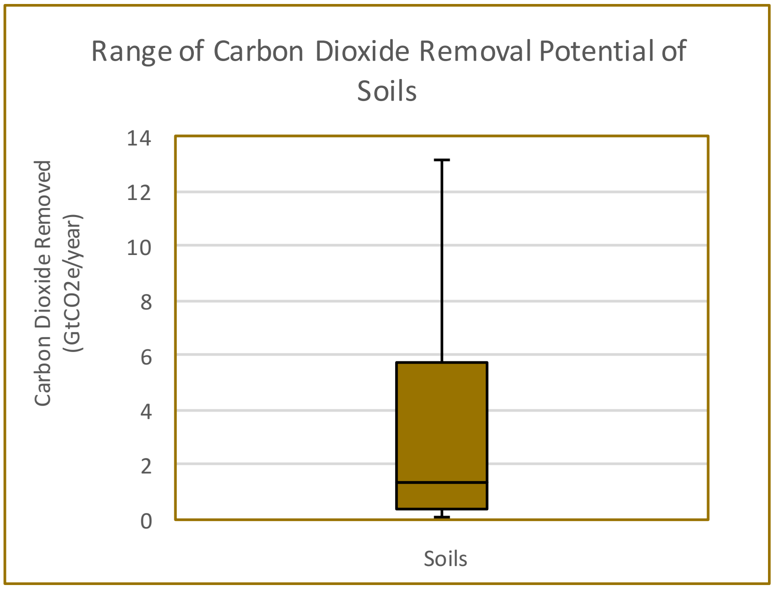

Figure 4-3: Graph of range of Carbon Dioxide Removal potential in Gt of carbon dioxide equivalency per year of Soils. Min: 0.1; 1st: 0.39; Median: 1.31; 3rd: 5.75; Max: 13.14 $GtCO_2e$/year.

Economic Analysis of Soils

Soil carbon sequestration is a CDR approach that relies on intentional land management targeted at increasing the storage of carbon as soil organic matter. Since carbon fluxes rely on natural processes which are highly variable and can easily be altered by management practice changes, reliable data on the cost of carbon sequestration through this methodology is lacking. Through our review of the literature, only one paper, (Smith et al., 2008), managed to provide an estimated cost for the implementation this active soil sequestration approach. However, within the spectrum of CDR implementation costs, soil carbon sequestration is expected to enter the lower range of costs once the value of crop sales is considered. The limited range of estimated costs is \$5.50 - \$11/tCO_2e. This is shown visually in Figure 4-4.

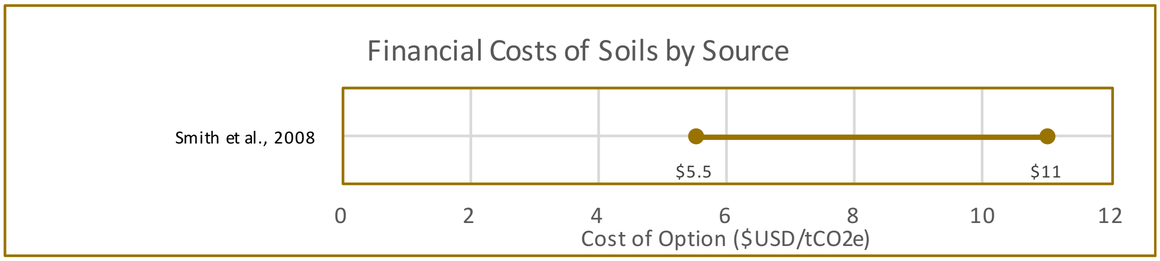

Figure 4-4: Graph of financial costs of Soils in 2015 US Dollars per tonne of carbon dioxide equivalency.

Due to the lack of estimates provided by source material, a quartile analysis could not be performed for this CDR option. Additionally, an analysis of which source and estimate were the most credible could also not be performed, as the only two estimates both came from Smith et al., 2008. Considering these restrictions, the research team decided to calculate the mean and median figure to determine an appropriate cost. The selected cost for soil carbon sequestration is $8.25/$tCO_2$e.

Geographic Restrictions

Soil carbon sequestration rates and total holding capacity are closely connected to the natural factors that are characteristic of a given location. The absolute amount of soil organic carbon is more closely tied to climate than vegetation type, indicating that climate plays a limiting factor in soil CDR potential (Jobbagy & Jackson, 2000). Theoretically, all soil could experience an increase in organic carbon content through plant activities near its surface or through geochemical weathering (Kohler et al., 2010).

However, the difference in sequestration rates across geographic regions is closely tied to variation in rainfall, temperature, and soil type. Jobbagy & Jackson (2000) indicated that total soil organic carbon increases with precipitation and clay content but decreases with temperature. Kahle et al. (2012) demonstrated that soils with higher iron oxide content tend to have less soil carbon. However, going beyond overall soil organic carbon content, the flux of carbon is based on the difference between production and decomposition of organic materials. In warm, humid climates, both production and decomposition accelerate, but decomposition increases at a relatively higher rate (Jobbagy & Jackson, 2000). Lack of precipitation constraints plant growth in arid regions, restricting soil carbon sequestration. In this way, factors related to the geographic location of soil and its flora can either restrict or enable soil carbon sequestration.

Policy Implications

Land use legislation provides a strong mechanism through which governments can promote soil carbon sequestration, especially on agricultural land. The Department of Agriculture, in the United States, administers land conservation programs including the Environmental Quality Incentives Program (EQUIP) and the Conservation Reserve Program (CRP) to provide payments for improved agriculture practices such as removing marginal agricultural land from production and creating buffer strips and windbreaks to reduce erosion and runoff (USDA, 2012). While CO_2 sequestration was not part of the original intent of CRP at its creation (Schahczenski & Hill, 2009), the program now monitors GHG sequestration and avoided emissions through reduced fuel and fertilizer application (USDA, 2012). Continuing this program and using subsidies to decrease the financial burden of conservation farming practices would cause more farms to implement practices that increase soil carbon, regardless of whether soil carbon sequestration is a stated concern.

Another example of a public policy promoting soil carbon sequestration is the “4 per 1000” Initiative. France launched “4 per 1000” as a side event to the COP21 meetings in 2015 to promote an increase in soil carbon for both environmental and food security reasons (Rhodes, 2016). The initiative was backed by the French Ministry of Agriculture and promoted practices such as minimizing bare soil, restoring degraded land, planting trees and legumes, and spreading manure and compost. The goal of “4 per 1000” is to increase topsoil by 0.4% annually through 2025 (4 Pour 1000, 2015). Although government initiatives like “4 per 1000” do not provide financial incentives for soil carbon sequestration, they serve as public awareness campaigns to promote improved soil management practices. While little data is available on this relatively recent initiative, future reports will indicate whether a global policy initiative can increase soil carbon sequestration on a global scale.

Benefits, Challenges, and Tradeoffs

Although reliable data on the cost of carbon sequestration through this methodology is lacking, the cost of soil carbon sequestration is projected to be a benefit. When considering life cycle costs, soil carbon sequestration is expected to enter the lower range of costs once the value of increased crop yields and crop or cattle sales are considered.

Even though the cost could be highly variable, the fact that soil CDR involves the cultivation of a product with market value makes it more likely that soil carbon will be relatively inexpensive compared to other, more technical CDR options. Each cropland or pasture has its own unique constraints which can change in a moment with a natural disaster or the decision to till a field. Therefore, very few efforts have been made to quantify the net cost or benefit of soil carbon sequestration, either for a specific location or as a generalizable estimate.

As a challenge, the use of arable land for conservation farming must be balanced with other mutually exclusive CDR options such as afforestation/reforestation and terrestrial-based accelerated weathering. Other CDR approaches such as biochar or BECCS could be combined with soil carbon sequestration, resulting in the need for a complex analysis of what percentage of carbon sequestration to attribute to each methodology (Eagle et al., 2012). Furthermore, soil carbon sequestration must be balanced with concerns for food production and biodiversity. Although these goals are not always mutually exclusive, optimizing for carbon sequestration sometimes decreases crop yields on farmland while cultivated land often reduces biodiversity when compared with other land uses (Nelson et al., 2009). However, implementing management practices targeted at increasing net soil carbon accumulation could provide an opportunity to remove carbon from the atmosphere through natural means and simultaneously achieve complementary goals of increased soil health and agricultural productivity.

Further Research

Although the storage of carbon in soils will happen naturally, further research is needed to understand how to increase the permanence of soil organic matter and the role of underlying soil type on total storage potential. Further research is also needed to compare the relative potential and cost of soil sequestration with other CDR approaches such as biochar or bioenergy with carbon capture and storage (BECCS). In terms of economics, clear data on implementation costs by region, crop, or management technique are lacking. To determine the costs associated with sequestering carbon in soils, more detailed analysis is needed to demonstrate potential benefits to farmers and agricultural lands.

Conclusion

In conclusion, a nominal estimate is that soil carbon sequestration could capture and store roughly 1.3 $GtCO_2e$/year at an approximate cost of \$8.25/tCO_2e. However, when all the literature is considered, the estimates range between 0.1 – 13 $GtCO_2e$/year at a cost between \$5.5 - \$11/tCO_2e. Further research regarding implementation impacts such as crop yields, economic costs of implementation, and CDR potential is necessary prior to mass implementation.

Chapter 5:

Biochar

Biochar

Introduction

Key Findings

- *Biochar is a demonstrated CDR option due to its implementation in some small-scale projects.*
- *Biochar has the potential to capture and store 0.23 GtCO$_2$e/year at an approximate cost of \$36/tCO2$_2$e.*
- *However, when all current literature is considered, the estimates range between 0.03 – 1.03 GtCO$_2$e/year ranging between a profit of \$149 and a cost of \$666/tCO2$_2$e.*

Biochar is the creation of charcoal from plant material, or biomass, through a process known as pyrolysis. This process consists of heating biomass at a relatively low temperature, 300°C - 800°C, in a low oxygenated environment, which prevents combustion. By preventing combustion, a thermochemical decomposition of the organic material occurs, leaving behind a carbon-rich charcoal. Biochar can be produced as either a primary product or, in the case of energy production, a secondary byproduct (Shabangu et al., 2014).

Biochar has been applied to agricultural soils for thousands of years to improve water and nutrient retention. On a molecular level, biochar provides more surface area for nutrients and beneficial microbes to adhere to (Jeffery et al., 2015). Biochar also can raise the pH level of soil, which can be beneficial in especially acidic soils. More recent studies have shown that the application of biochar to soils can reduce nitrogen leaching by 60% (Singh et al., 2010). In some studies, the application of biochar has improved yields by 38-45%. This can be interpreted as a 20% savings in fertilizer use and a 10% savings in irrigation and seeds (Kung et al., 2013). Today, the primary uses for biochar include soil abatement, the use in chemical and industrial manufacturing, and, more recently, a way of sequestering carbon from the atmosphere.

The Process of Producing Biochar

The basic definition of photosynthesis is that with the energy from the sun, plants take in carbon dioxide (CO_2) and water, and convert them to form carbohydrates (sugars). This means that carbon is a building block of all plant material. However, when plant material is heated, thermal decomposition begins to occur. Chemical bonds start to break down, and in a low oxygenated environment, carbon bonds are some of the last to break. If controlled, a carbon rich-char will be left behind.

Chapter 5: Biochar

The production of biochar and its use to improve soil conditions has been occurring for thousands of years. The process to produce biochar can be as simple as setting a field on fire. However, a more controlled method involves burning biomass in a kiln or enclosed container. This leaves behind the biochar. This biochar will then decompose much slower than the surrounding organic material. Burying or applying Biochar to soil prevents the carbon from returning to the atmosphere in the form of CO_2, which would naturally occur in the decomposition process through respiration by organisms breaking down organic material.

The Production of Biochar

The overall process consists of the following steps:

1. Plant material, also known as biomass, needs to be collected. This plant material can be anything from agricultural and crop waste, to woody plant material.
2. The biomass will then be heated in a controlled, low oxygenated, environment to a temperature between 300°C - 800°C. This is known as pyrolysis.
    a. The pyrolysis process can take place in conjunction with the production of biochar and bioenergy products, such as syngas and bio-oil, which could provide alternative energy sources for electricity generation and heating application (Kung et al., 2013).
    b. The pyrolysis processes can be classified into fast and slow according to the processing temperature (higher vs. lower) and biomass residence time (shorter vs. longer). Fast pyrolysis can generate more bio-oil and less biochar than slow pyrolysis (Woolf et al., 2010).
3. The carbon-rich biochar that is left can be slowly released underground, or more commonly, used to improve soil quality by spreading it over agricultural land.

A schematic of the fast pyrolysis process extracted from the USDA website is shown in Figure 5-1. It explains the mass and energy flow balance of the biomass, which is converted through pyrolysis to yield solid products, sand, biochar, and bio-oil. Syngas produced is subsequently transported and used to fuel the pyrolysis process, sand furnace, and biomass pretreatment, while bio-oil is transported to a storage tank.

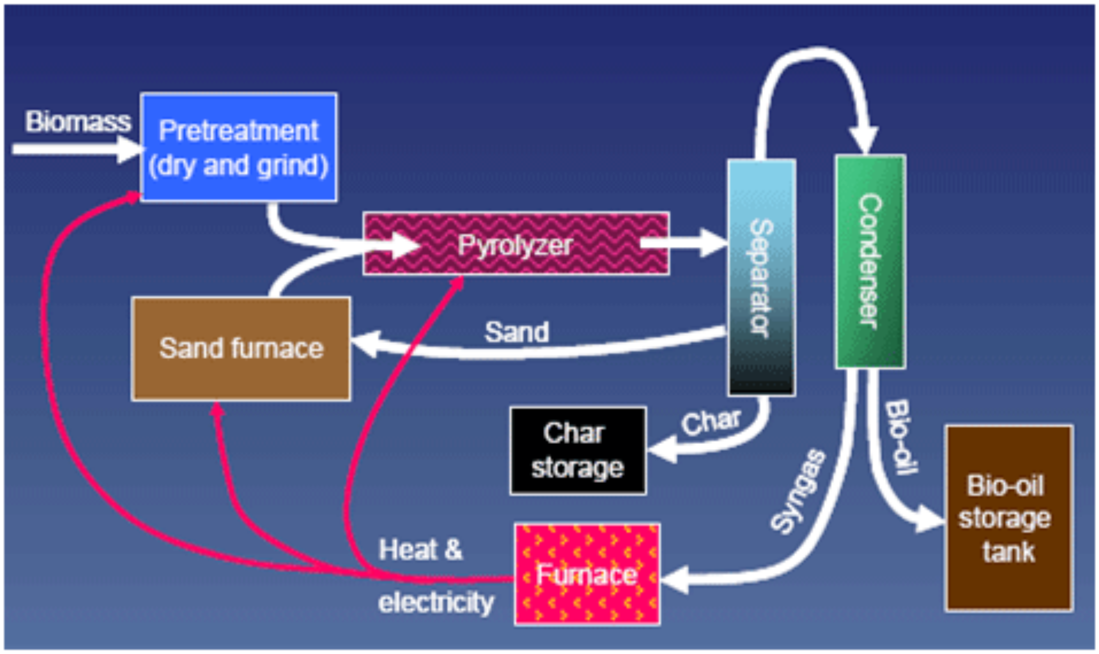

Figure 5-1: Schematic of the fast pyrolysis process. Image from USDA-ARS, 2016.

Carbon Dioxide Removal Potential of Biochar

Although the carbon dioxide removal (CDR) potential is highly dependent on the variables that go into biochar production and application, it is estimated that biochar has the potential to sequester and store between 0.03-1.03 $GtCO_2e$/year in different regions around the world. The biomass feedstock sources compared are corn stover, yard waste, and a switchgrass energy crop. This range of feedstock provides insight into the climate change impacts, as well as economic costs, between the use of biomass "waste" resources and those crops used solely for bioenergy. The CDR potential of biochar is listed by source in Figure 5-2.

The variation in CDR potential, 0.03 - 1.03 $GtCO_2e$/year, is due to the wide range of major assumptions used by different studies. Key variables that affect the potential CO_2 reduction include feedstock material, availability of biomass, the temperature at which the pyrolysis process took place, and what incentives were in place to incentivize application. Additionally, biochar is created from biomass and there is a limit to how much biomass can be collected at one time within a radial distance from the pyrolysis plant. On average, 40% of any biomass is made up of carbon. Therefore, the theoretical limit for extraction of carbon from biomass is reflected in this percentage (Galinato et al., 2011).

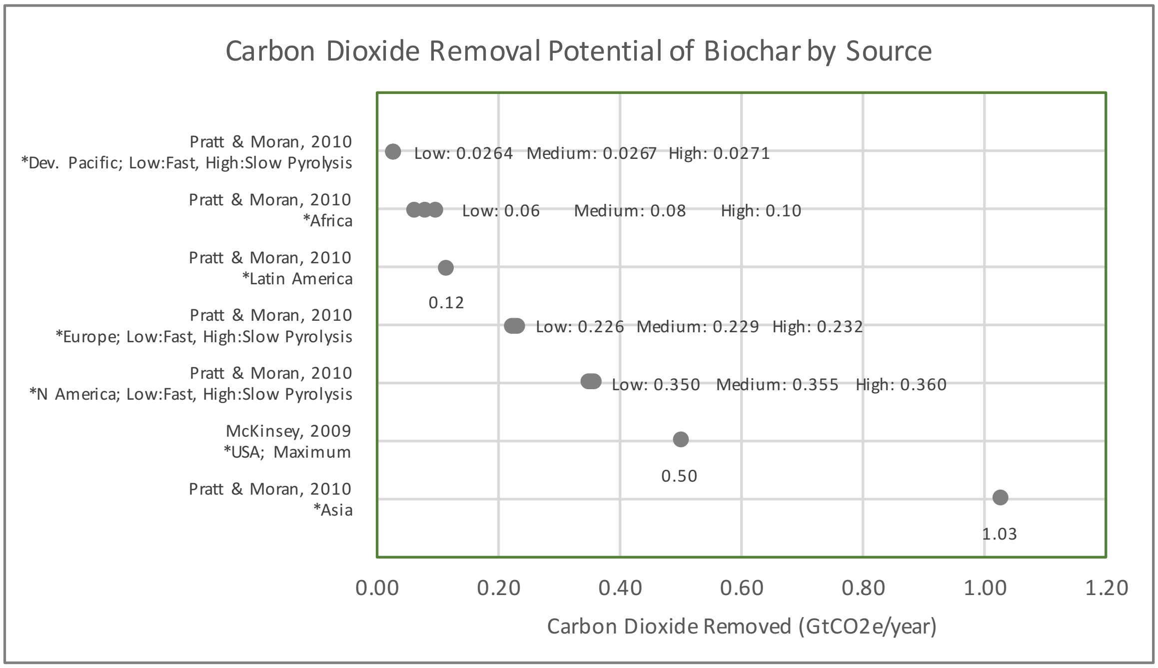

Figure 5-2: Graph of Carbon Dioxide Removal Potential in Gt of carbon dioxide equivalency per year of Biochar. *Key assumptions made by the original author(a) or this research team are listed below the source.

Within the literature reviewed, both the highest and lowest estimate of carbon emission abatement came from Pratt & Morgan's (2010) estimates. They predicted that the potential in Asia could reach up to 1.03 Gt by 2030, while that in Developed Pacific will only be 0.03 Gt over the same period. This is mainly due to their assumption that 10% of Asia will be involved in biochar projects by 2030. Due to the high cost of modern pyrolysis systems, developing countries tend to use more simplistic methods for creating biochar. These methods have been used for centuries but tend to be dirtier and less efficient. Modern pyrolysis plants can generate bio-oil and biogas. These biofuels are produced when a "fast" pyrolysis process is used, versus a "slow" pyrolysis process which produces more biochar (Sohi et al., 2009). Therefore, fast pyrolysis is particularly favored in Europe. With incentives for bioenergy used for electricity generation and active carbon markets, these countries have the potential to maximize the benefits gained by biochar.

As can be seen in Figure 5-2, there are substantial variations between the estimates/range of estimates from the studies, 0.03 – 1.03 $GtCO_2e$/year, therefore, further analysis was conducted. Using a quartile analysis, 50% of the data sources suggest that biochar could sequester and store between 0.07 - 0.35 $GtCO_2e$/year with a median figure of 0.23 $GtCO_2e$/year. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 5-3.

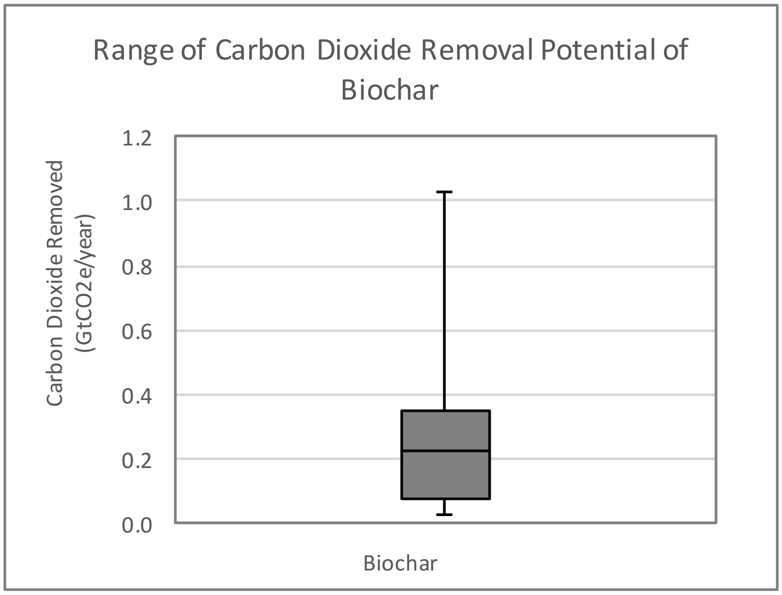

Figure 5-3: Graph of the range of carbon dioxide removal potential in Gt of carbon dioxide equivalency per year for Biochar. Min: 0.03; 1st: 0.07; Median: 0.23; 3rd: 0.35; Max: 1.03 $GtCO_2e$/year.

Economic Analysis of Biochar

Biochar has been used for thousands of years to improve soil quality, with the added benefit of storing carbon in the soil for hundreds to thousands of years. As stated earlier, the variables that affect the production of biochar often affect the cost, such as the different cost of feedstocks (energy crop vs. yard waste), pyrolysis technologies (advanced pyrolysis vs. stove), and transportation cost. Any differences in these variables can change the carbon content, absorption qualities, or the pH of biochar, thus causing positive or negative effects on plant growth in the areas treated with biochar. The potential for improved plant growth, or crop yield, can cause the net cost of biochar to become negative when profits are included from the increased crop yields. Depending on limitations with feedstock availability, transportation distances of both feedstock and biochar, and application of biochar to soils, the cost of biochar ranges from a profit of approximately \$149 to a cost of \$666/tCO_2e. Estimated financial costs of biochar can be seen by source in Figure 5-4.

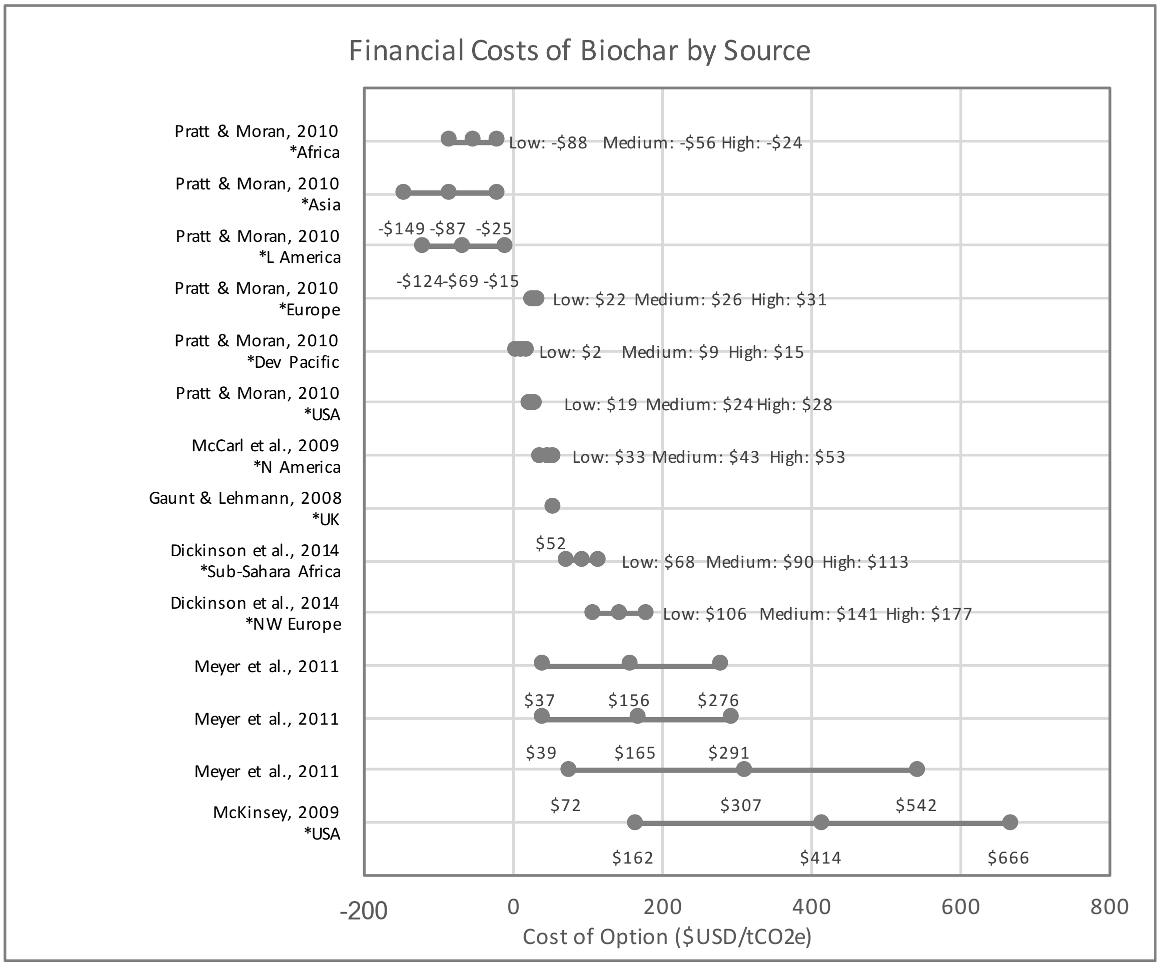

Figure 5-4: Graph of financial costs of Biochar in 2015 US Dollars per tonne of carbon dioxide equivalency. *Key assumptions made by the original author (s) or this research team are listed below the source.

As can be seen in Figure 5-4, there is substantial variation among the estimates, from a profit of $149 to a cost of $666/tCO2$_2$e. Therefore, further analysis was conducted. Based on a quartile analysis from all sources, 50% of the estimates suggests biochar costs between $5 - $149/tCO2$_2$e with a median cost of $36/tCO2$_2$e. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 5-5.

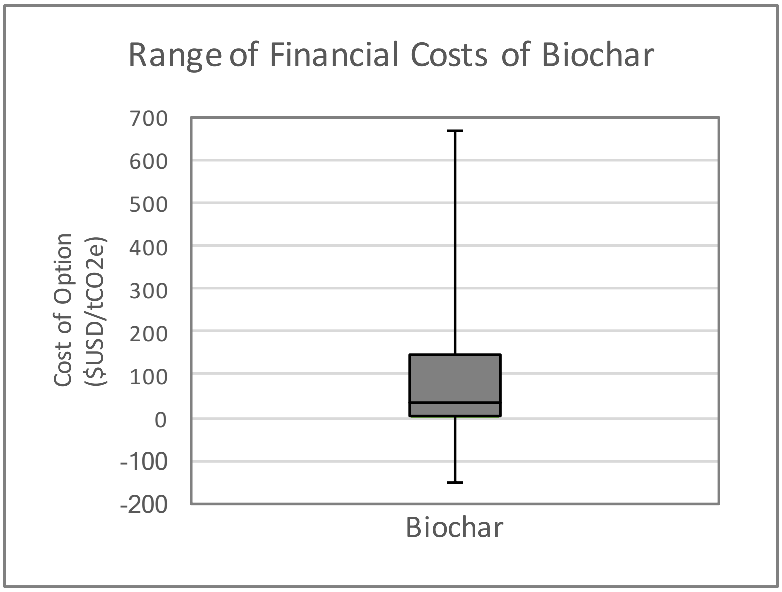

Figure 5-5: Graph of range of financial costs of Biochar in 2015 US Dollars per tonne of carbon dioxide equivalency. Min:-149; 1st: 5; Median: 36; 3rd: 145; Max: 666 USD/tCO_2$e.

Geographic Restrictions

Biochar can be produced and applied in essentially every part of the globe. However, the level of biochar, and thus carbon, that can be created from biomass depends on the type of biomass used in the pyrolysis process, as well as, the temperature used during pyrolysis. Also, biochars created from different biomasses have varied properties in regards to soil abatement. Therefore, restrictions apply to what type of biomass, whether it is coconut shells, corn husks, or woody plants, are used to make biochar in certain regions of the globe. Soil composition also plays a large part in the effectiveness of the desired soil abatement properties of biochar. Coarse to medium textured soil types have been found to benefit the most from the application of biochar. However, other soil types have shown to be adversely affected by the application of biochar. Therefore, soil type in a region greatly affects whether or not biochar can, and should, be applied to the soil (Lehmann et al., 2011).

Policy Implications

The current market price for biochar is approximately $1500/t, according to generic price searches through Google.com completed online in 2016. With application rates ranging from 1 to 60 t of biochar/ha (Dickinson et al., 2015), many of these application rates become uneconomical for farmers. If biochar production as a byproduct is a result of increases in bioenergy production, then the increase in supply will bring the price of char down. This would address the current high costs associated with biochar application, however, it would not address the uncertainties that farmers might have in regards to the adverse effects that biochar could potentially have on their soil. If there were better, more concise, information on effects of biochar from different feedstocks, and its effect on different soil types, this might encourage farmers to consider the benefits of biochar. Additionally, industrial agriculture, especially organic farms trying to use fewer fertilizers, may find biochar a more attractive option if subsidies and information for biochar were more readily available.

Benefits, Challenges, and Tradeoffs

Biochar has numerous benefits, including carbon sequestration, soil fertility improvement, biofuel/bioenergy production, and disposal of organic waste. However, these benefits could turn into risks given the uncertainty that surrounds overall net GHG emissions. Uncertain factors include the life cycle carbon emissions of the collection and transportation of biomass and biochar, the environmental and health risks associated with more primitive methods of the pyrolysis process, and the potential of biochar reducing crop yields if applied incorrectly (Dickinson et al., 2015; Jeffery et al, 2015; McCarl et al., 2009).

Among all the trade-offs, two of them are discussed heatedly. The first trade-off is whether the land for growing food crops or conservation should give way to biomass production (Jeffery et al., 2015). Although it is appealing to convert biomass into biofuel, and thus create biochar as a byproduct, the land that would be used for food production might begin to decline (Smith, 2013). On the flip side, there is increasing interest in using crop waste as a source of biomass feedstock for biochar production (Tuck et al., 2012). This would balance the trade-offs between needing to use agricultural lands for crop production, and gaining the benefits from biochar production.

The second concern, discussed in Dickinson et al. (2015), is that the life cycle carbon emissions of several facets of biochar production, such as pyrolysis, feedstock transport, and harvesting, which may offset the carbon sequestered by biochar. Although the energy produced during pyrolysis can be used to replace fossil fuels, the energy source for starting the pyrolysis system often come from coal or other carbon-intensive fuels, especially in developing countries. This could offset the carbon captured within the entire process. Thus, from a life cycle perspective, minimal trade-offs exist if pyrolysis has an efficient and appropriate energy source, as well as, transportation distances, biochar pyrolysis systems, and storage can be optimized.

Further Research

Compared to the other seven CDR approaches examined in this report, biochar has existing fundamental and first-hand research regarding its viability, benefits, costs, and carbon removal potential. However, continued research is still needed to identify and understand the numerous variables that go into biochar production, and application, for it to become a viable means to sequester carbon from the atmosphere. Further research should focus on adopting systematic models to minimize the trade-offs through producing sustainable biochar and providing biochar that will improve soil conditions upon application.

In order to scale up the biochar system, it is important to produce biochar that is made from a sustainable feedstock. Additionally, it is important to achieve the appropriate temperature levels for the pyrolysis process from a sustainable fuel or heat source. Furthermore, the relationship between biochar production and other related bioenergy industries, with the potential policy issues associated with those processes, must be addressed prior to mass implementation.

Conclusion

In conclusion, a nominal estimate is that biochar could capture and store roughly 0.23GtCO$_2$e/year at an approximate cost of \$36/tCO2$_2$e. The estimates from the literature range between 0.03–1.03 GtCO$_2$e/year at a price between a profit of \$149/tCO2$_2$e to a cost of \$666/tCO2$_2$e. Further research regarding impacts such as ecological effects on soils, economic costs, effects on crop yields, and CDR potential are necessary before mass implementation of biochar.

Chapter 6:

Accelerated Weathering

Accelerated Weathering

Introduction

Accelerated weathering is a speculative carbon dioxide removal (CDR) option that enhances, or accelerates, chemical weathering processes that naturally occur in nature. Carbon dioxide (CO_2) is removed from the atmosphere through a reaction with water and calcium, magnesium, or iron silicate minerals such as olivine, wollastonite, serpentine, or limestone to produce soluble bicarbonate ions and a solid byproduct (Rau & Caldeira, 1999). Even though it is still in the development phase, laboratory tests in the United States and Finland have tested the theoretical assumptions underlying the potential for CO_2 sequestration through accelerated weathering (Giannoulakis, 2014).

Key Findings

- *Accelerated weathering is a speculative CDR option due to limited pilot testing and uncertain environmental impact.*
- *Accelerated weathering has the potential to capture and store 3.7 Gt CO_2e/year at an approximate cost of \$70/tCO_2e.*
- *However, when all current literature is considered, the estimates range between 0.001 – 18 GtCO_2e/year at a cost between \$21 - \$537/tCO_2e.*

While accelerated weathering encompasses the general concept of enhancing natural chemical processes, there are several specific approaches to applying accelerated weathering as a CDR approach. This paper will include references to four approaches: wet carbon mineralization, enhanced carbon dissolution, soil mineralization, and seawater injection into basalt rock. These options vary in the extent of research that has been done and the level of confidence that experts place in their practical application (McLaren, 2012). Wet carbon mineralization, which provides a productive use for industrial waste such as cement kiln dust or coal fly ash, has received increasing interest since it can be implemented with a limited physical footprint and can reduce both CO_2 emissions and industrial waste (Kirchofer et al., 2013).

The Accelerated Weathering Process

Accelerated weathering is based on a chemical reaction that can be carried out with several different reactants and in either *in situ* or *ex situ* settings. The main minerals considered as potential source material for accelerated weathering are magnesium, calcium, and iron silicate minerals (Gerdemann, 2007). These include naturally occurring minerals with similar chemical composition such as olivine, serpentine, wollastonite, and calcium carbonate (Giannoulakis, 2014; Matter et al., 2016; Rau et al., 2007). Some industrial waste products high in magnesium or calcium-containing silicates have been considered for use. Coal fly ash, steel-making slag, and cement kiln dust have all been studied as possible inputs (Kirchofer et al., 2012).

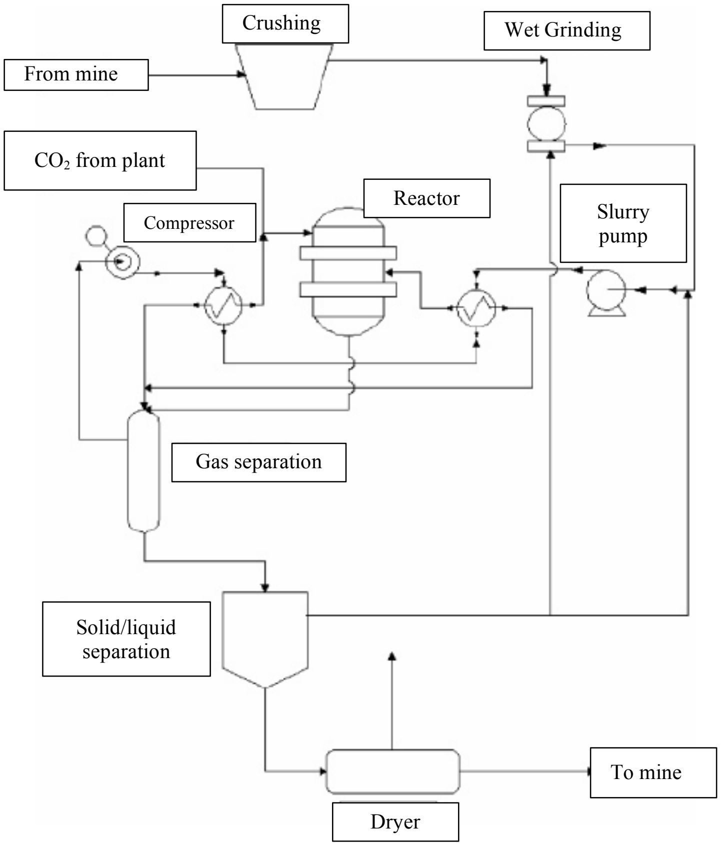

Figure 6-1: Mineral carbonation. Image adapted from Gerdemann, 2007.

The basic chemical reaction depends on the source mineral. For calcium carbonate (limestone) it is:

$$CO_2 + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2(HCO_3^-)$$

Alternative potential reactions, using forsterite and anorthite, respectively, have been observed both in the laboratory and nature (Oelkers, et al. 2008):

$$Mg_2SiO_4 + 2CO_2 = 2MgCO_3 + SiO_2$$

$$CaAl_2Si_2O_8 + CO_2 + 2H_2O = CaCO_3 + Al_2Si_2O_5(OH)$$

Depending on the source materials used, the target stable carbonate resulting from the reaction is often calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_{2)}$ or Magnesite ($MgCO_3$). The most well-studied accelerated weathering process, wet carbon mineralization, is explained below and modeled in Figure 6-1.

The Accelerated Weathering Process

As envisioned by (Gerdemann et al., 2007), the overall process based on wet mineral carbonation would consist of the following steps:

1. Pretreatment: source mineral, from either industrial waste or mining, is ground to the optimal size and heated to the optimal temperature. CO_2 gas is purified and pressurized, if needed.
2. Slurry pumping: the pretreated mineral is mixed with water or a saline solution, based on optimal pH level, and pumped to the reactor.
3. Reaction: a pressurized stream of CO_2 is mixed with the mineral slurry in an agitator, resulting in mineral carbonation.
4. Separation: gas and solid separators are used to a) separate out unused CO_2 for reuse and b) separate water for purification and reuse from the carbonate product and residue.
5. Storage: the carbonate and solid residue are transported to a storage location.

Additionally, accelerated weathering in the form of enhanced carbon dissolution can be achieved by dissolving CO_2 in ocean water to produce carbonic acid, which is then reacted with mineral carbonate to produce dissolved calcium ions and bicarbonate in an alkaline mixture (Rau & Caldeira, 1999). Soil carbonation, as proposed by Kohler (2010) involves pulverizing a mineral such as olivine and spreading it over a large geographical region of land or ocean. This would increase the surface area of the mineral in contact with atmospheric CO_2, allowing for a faster reaction than would occur with the same amount of olivine in a rock outcropping. The final proposed CDR process involving accelerated weathering is the injection of seawater into basalt or peridotite rock, which contain olivine. The same reaction process would occur as described for wet mineral carbonization, with the products of the reaction piped out of the rock formation and either dissolved in the ocean or transported for storage (Keleman & Matter, 2008).

Carbon Dioxide Removal Potential of Accelerated Weathering

The projected CDR potential of accelerated weathering is highly dependent on the process considered and its underlying assumptions. Accelerated weathering that depends on large areas of land or water to scatter silicate minerals is limited by geographic extent (Kohler et al., 2010). Wet mineral carbonation processes that use silicate-based industrial byproducts as raw material are dependent on the quantity of those products available. In the model provided by Kirchofer (2012), estimates were based on a combined 778 Mt/year of lime, sand, and gravel mined in the U.S. Seawater injection into basalts is limited by the range of basalt formations within the tidal zone (Keleman & Matter, 2008). As a speculative CDR option still in the development phase, the estimates available are all based on a specific region instead of reflecting global potential. No study reviewed in this report included estimates for the entire world, either for a single type of accelerated weathering or for all applications. Since the applications of these four accelerated

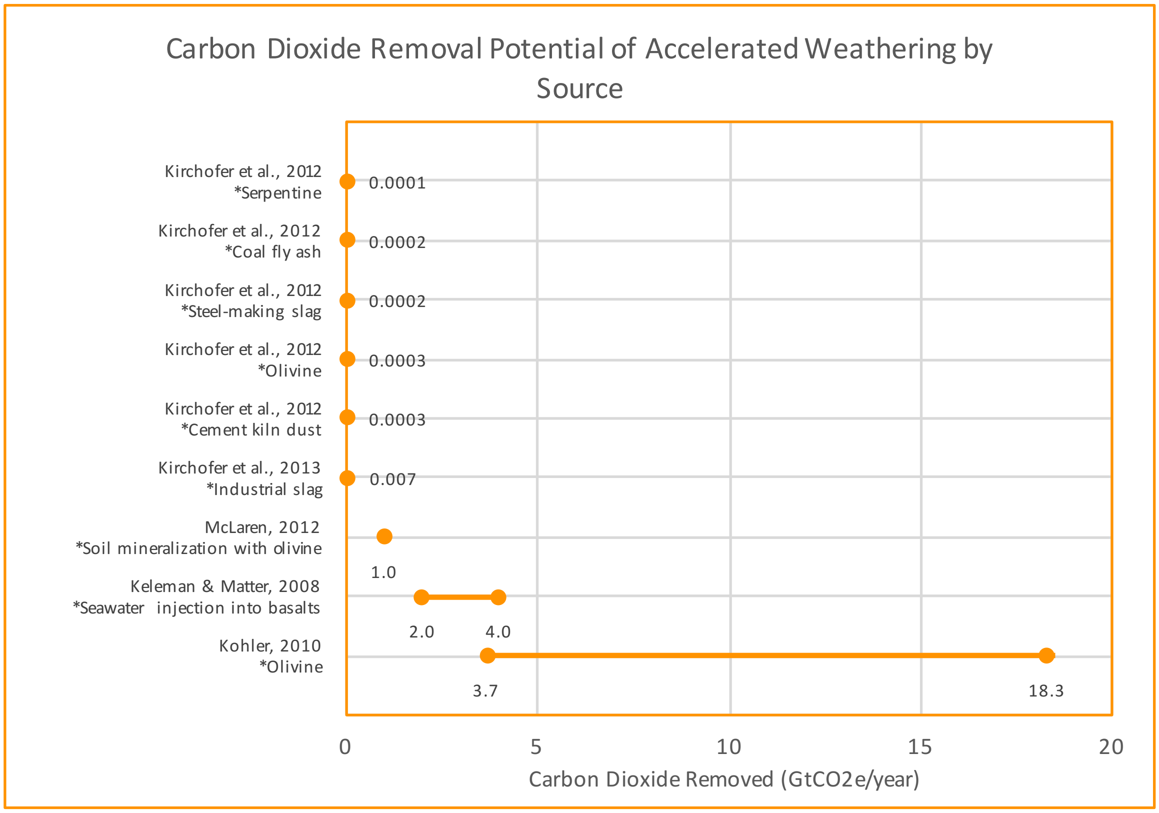

Figure 6-2: Graph of Carbon Dioxide Removal Potential in Gt of carbon dioxide equivalency per year of accelerated weathering. *Key assumptions made by the original author(s) or this research team are listed below the source.

weathering process are not mutually exclusive, it is conceivable that all four could be executed to some degree as CDR options. In the same way, the difference in processes, required inputs, and required land area lead to different magnitudes of implementation potential. Based on available research, the sequestration and storage potential of accelerated weathering options is estimated between 0.001 Gt and 18 $GtCO_2e$/year. The CDR potential of accelerated weathering is listed by source in Figure 6-2.

The variation in estimates of CDR potential stems from differences in the underlying assumptions for each study. Kirchofer (2012) based separate estimates on the availability of each of four industrial byproducts and a naturally-occurring mineral within the U.S. In a subsequent study, Kirchofer (2013) based calculations on an estimate of the sand and gravel mined on an annual basis in the U.S. McLaren (2012) compiled estimates based on a range of CDR options and estimated a central figure for soil mineralization with olivine. Keleman & Matter (2008) based their estimates on known peridotite deposits in Oman but recognized that additional sites exist in Papua New Guinea, New Caledonia, and the east coast of the Adriatic Sea (Keleman & Matter, 2008).

As can be seen in Figure 6-2, there is substantial variation between the estimates from the studies, ranging from 0.0001 to 18 $GtCO_2e$/year. However, accelerated weathering options are not mutually exclusive, and the most realistic option would be a data point that accounts for the real possibility of achieving some sequestration through a variety of accelerated weathering processes. Through further analysis, the realistic value of 3.7 $GtCO_2e$/year was selected. This figure is higher than the estimates for wet carbon mineralization in the U.S. alone or low estimates of the potential of seawater injection into basalts. However, it also does not depend extensively on soil carbonation alone. As a speculative option, accelerated weathering has potential for future CDR, but the scale of that potential is still uncertain.

Economic Analysis of Accelerated Weathering

Accelerated weathering is a CDR approach that has been proposed and modeled with minimal field or pilot tests. Because most estimates of accelerated weathering's costs are based on theoretical assumptions, they present a wide range of possible costs. Wet mineral carbonation processes demonstrate the greatest cost variation based on mineral used. In the same study by Gerdemann (2007) olivine-based processes cost \$68/tCO_2e while the same process utilizing wollastonite costs \$537/tCO2e. All accelerated weathering costs are estimated between \$21 and \$537/tCO_2e. Estimated financial costs of accelerated weathering are listed by source in Figure 6-3.

Of the estimates provided, Gerdemann (2007), Rau (2007) and Rau (2013) are based on wet carbon mineralization. McLaren (2012) and Kohler (2010) are based on soil mineralization, Rau & Caldeira (1999) is based on enhanced carbon dissolution.

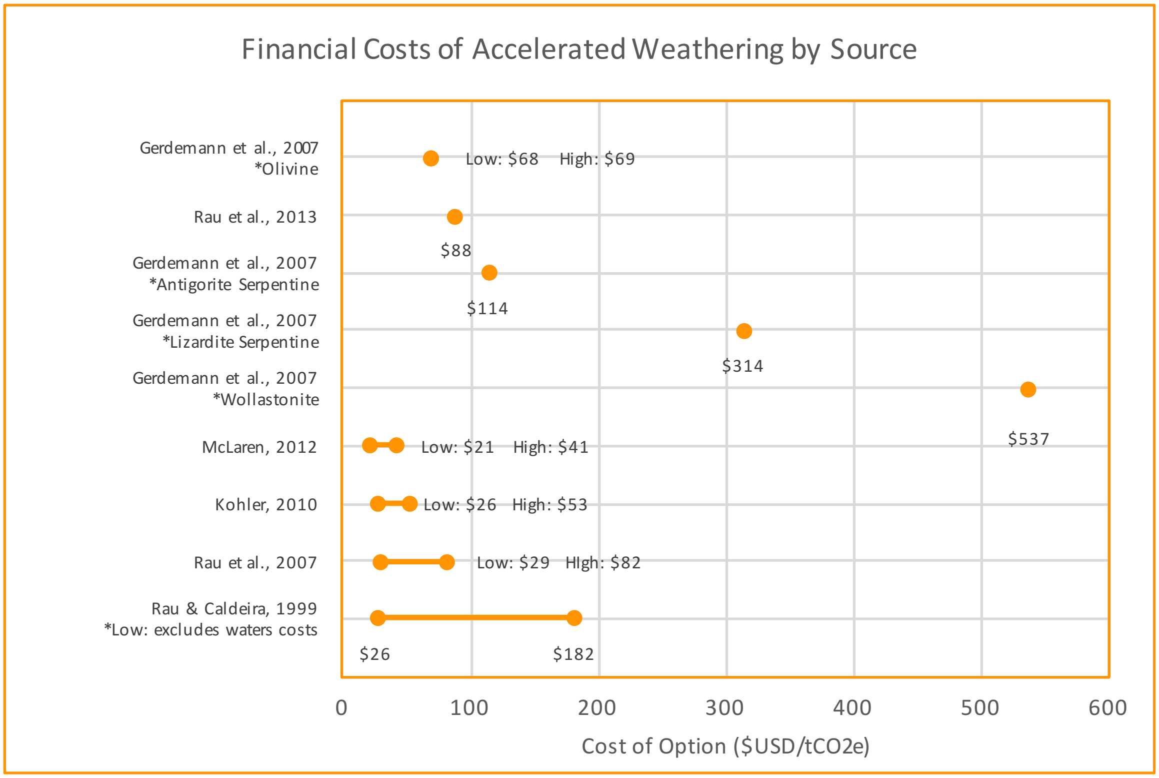

Figure 6-3: Graph of financial costs of accelerated weathering in 2015 US Dollars per tonne of carbon dioxide equivalency. *Key assumptions made by the original author(s) or this research team are listed below the source.

Again, as can be seen in Figure 6-3, there is substantial variation among the estimates, \$21 - \$537/tCO_2e. Therefore, further analysis was conducted. Based on a quartile analysis from all sources, 50% of the estimates suggests accelerated weathering costs between \$32 - \$108/tCO_2e with a median cost of \$69/tCO_2e. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 6-4.

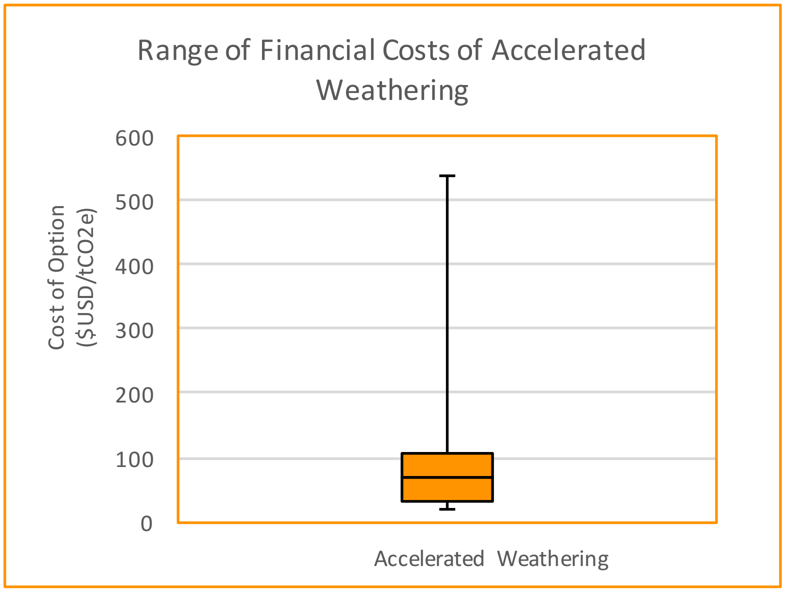

Figure 6-4: Graph of range of financial costs of accelerated weathering in 2015 US Dollars per tonne of carbon dioxide equivalency. Min: 21; 1st: 32; Median: 69; 3rd: 108; Max: 537 $USD/t CO_2e.

Geographic Restrictions

The geographic location where accelerated weathering can be implemented depends predominantly on the processes used. Seawater injection into basalt rock must occur in coastal regions where basalt or peridotite rock naturally occurs (Keleman & Matter, 2008). Soil mineralization is recommended only in remote river basins. Kohler (2010) suggested the Amazon and Congo Rivers as potential options.

Both wet carbon mineralization and enhanced carbon dissolution must occur in areas with access to large quantities of water. Enhanced carbon dissolution is ideally pursued at or near the ocean to prevent pumping water long distances (Rau & Caldeira, 1999). Wet mineral carbonation could technically be pursued anywhere that water is abundant, but coastal regions have been suggested as optimal since the resulting bicarbonate solution could then be injected into the ocean (Rau, 2008). Gerdemann (2007) recommends locating plants near regions where ultramafic minerals could be mined. Kirchofer (2012) assumes that wet mineral carbonation will occur within 200 miles of source material. All these considerations show that, while mineral carbonation could be implement anywhere, it will likely be in coastal regions with abundant access to water as well as mineral inputs.

Policy Implications

Policies related to the cost of water use and requirements for industrial waste disposal could affect the implementation of accelerated weathering. Raul & Caldeira (1999) explicitly recognizes that the cost of water would have a drastic effect on the ability to implement low-cost CDR through accelerated weathering. If government policies favor free access to ocean water for accelerated weathering, it would make wet mineral carbonation more economically feasible. Likewise, increased dumping costs for industrial waste could create a market for the use of ideal inputs such as coal fly ash, steel-making slag, and cement kiln dust.

On the other hand, soil mineralization and seawater injection into basalts are two unproven options that would depend on government approval. Spreading olivine or another mineral over a region large enough to have a measurable CDR result would likely require permission to use government-owned protected areas. In the same way, use of basalt rock in tidal areas would require government permission, so implementation of this technology would be contingent on consent from one of the countries where basalt or peridotite rock is located (Keleman & Matter, 2008; McLaren, 2012).

Benefits, Challenges, and Tradeoffs

Accelerated weathering can provide broader benefits beyond its CDR potential through byproducts and the relatively low impact of some processes such as wet carbon mineralization. Most forms of accelerated weathering involve carbonation of water, which creates an alkaline bicarbonate solution that can be injected into the ocean. Studies have recommended the bicarbonate as an option to counteract ocean acidification (Rau & Caldeira, 1999). On land, the solid byproducts of wet carbon mineralization can be used as a backfill for mining operations. In this way, they can help to restore natural land contours and avoid inserting more material into landfills (Giannoulakis, 2014). Furthermore, when industrial byproducts are used as mineral sources, the disposal of those products as industrial waste is reduced (Kirchofer et al., 2013).

Many of the accelerated weathering processes are yet untested, so concerns remain regarding potential negative consequences, especially for land-based options. Additionally, accelerated weathering increases the alkalinity of the water or land in which it is implemented. A minor increase in some areas might be beneficial (Rau, 2008), but concern arises from the potential for drastic increases in pH levels. Kohler (2010) suggests spreading an olivine powder over an area of

50.83 billion m^2 in the Amazon River basin and 36 billion m^2 in the Congo River basin. Beyond the challenge of covering such an expanse, Kohler recognizes the possibility of raising the pH level to 6.8 in the Amazon region and 6.7 in the Congo River basin, which would have a drastic impact on wildlife.

Further Research

Further research on accelerated weathering should focus on determining the scalability of laboratory-based wet mineral carbonation processes and factoring economic considerations to determine the minimum efficient scale for siting an accelerated weathering plant near a power plant or source of industrial waste materials.

Conclusion

In conclusion, a general estimate is that accelerated weathering could capture and store about 3.7 $GtCO_2e$/year at an approximate cost of \$69/tCO_2e. However, when all current literature is considered, the estimates range between 0.001 – 18 $GtCO_2e$/year at a cost between \$21 - \$537/tCO_2e. Further development of scalable pilot projects along with research on full environmental impact and scale of potential implementation are necessary before mass implementation.

Chapter 7:

Direct Air Capture (DAC)

Direct Air Capture (DAC)

Introduction

Direct Air Capture (DAC) involves removing carbon dioxide (CO_2) from the ambient air using a mechanical device. DAC is sometimes referred to as artificial trees. In DAC, air is forced through the DAC system which captures CO_2 and concentrates it into an easily stored form (Socolow et al., 2011).

Key Findings

- *DAC is considered a speculative option due to uncertainties in the literature and lack of large-scale demonstration projects.*
- *DAC has the potential to sequester and store 1 GtCO_2e/year at an approximate price of \$345/tCO_2e.*
- *However, when all current literature is considered, the estimates range between 0.0004 – 16 GtCO_2e/year at a cost between \$30 - \$1,050/tCO_2e.*

While a new concept for atmosphere wide implementation, removal of CO_2 from the ambient air has occurred in small spaces like submarines and spaceships for decades through monoethanolamine scrubbers (Lackner et al., 2012). DAC is still in the research and development stage, as such, the estimates provided in this chapter should be recognized as estimates based on models and limited project data (Lackner et al., 2012).

The Dir Air Capture (DAC) Process

There are two primary methods to capture CO_2, through an aqueous chemical sorbent or solid sorbents which act as filters. This captured CO_2 can be used as an input into another industry or stored geologically (Socolow et al., 2011).

For the chemical sorbent DAC system, the aqueous solution that is bonded with CO_2 can come in many forms. The most commonly mentioned are certain hydroxides such as sodium hydroxide (NaOH) (Socolow et al., 2011). This paper will focus on NaOH based solutions due to the prevalence of this system in the published literature (Holmes et al., 2012; Keith et al., 2006; Mazzotti et al., 2013; Socolow et al., 2011; Stolaroff et al., 2008; Zeman et al., 2014). The highly-referenced American Physical Society (APS) report on DAC, whose lead author is Socolow, assumed a NaOH based system for their analysis. Ambient air enters an absorber where the NaOH solution is located and CO_2 binds with the chemical solution to create Na_2CO_3. This solution travels to the precipitator to separate the CO_2 and regenerate the NaOH. This is done by adding calcium to produce $CaCO_3$ and NaOH. The

NaOH is sent back to the absorber. The CO_2 is separated from the calcium by exposure to high temperatures, over 800° C, and is the most energy intensive step (House et al., 2011). The remaining CaO enters the slacker and is combined with water to re-create $Ca(OH)_2$. The CO_2 is released and compressed into a concentrated stream that is ready for transport to a storage site (Socolow et al., 2011). See Figure 7-1 for an illustrative account of the process.

The DAC Process

As analyzed by (Socolow et al., 2011), the aqueous sorbent process would consist of the following steps:

1. A fan forces air through the contactor unit of a DAC system, the CO_2 binds to a sorbent (NaOH in this case).
2. The sorbent and CO_2 mixture is transferred to a precipitator which adds calcium to separate the CO_2 from the sorbent.
3. The calcium and CO_2 solution is heated to 800° C to separate the calcium and CO_2.
4. The CO_2 is then compressed into a concentrated stream ready for transport.

As envisioned by (Lackner et al., 2010), the solid sorbent process would consist of the following steps:

1. Air passes through a solid sorbent of negatively charged carbonate ions. The nanopores of the material capture CO_2.
2. The CO_2 laden sorbent is removed and enters a secondary chamber for CO_2 concentration.
3. The chamber is vacuum sealed and water is administered to the sorbent.
4. A concentrated water and CO_2 mixture is created, ready for transport.
5. The solid sorbent is replaced, ready to collect more CO_2.

While not as researched as aqueous capture solutions, the second DAC system is based on solid sorbents. One of the big advantages of solid sorbents is that they trap more gas per unit of energy than other proposed systems (Lackner et al., 2010). For solid sorbent DAC systems, air is pushed through a solid filter of negatively charged carbonate ions with nanopores which attract CO_2 when dry. A circular track holds the filters in place and allows the filters to revolve around the base. The filters are dropped down into a secondary area. The area is vacuum sealed and water is sprayed to remove the CO_2 from the filter and forms a concentrated stream of CO_2. The cleaned filters are then placed back in the capturing area to begin the process again. Even though such DAC systems are small, they can be mass produced to utilize economies of scale and can create a big impact, Lackner (2010) envisions 10 million units the size of a shipping container, removing 5 ppm/year. One of the biggest benefits of solid sorbents is that the energy penalty associated with the high temperature used in aqueous DAC systems is removed (Lu et al., 2013).

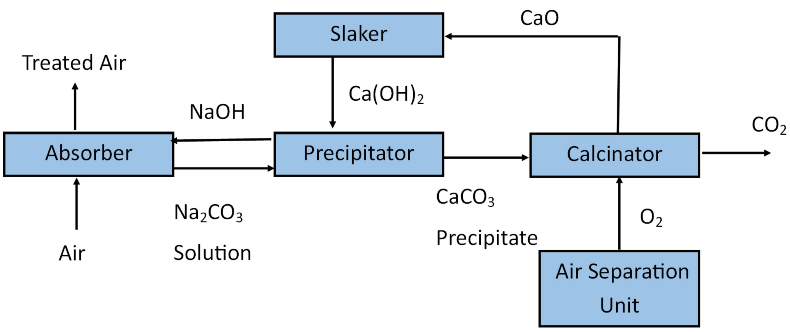

Figure 7-1: The steps of an aqueous NaOH solution DAC system. Image adapted from Socolow et al., 2011.

Carbon Dioxide Removal Potential of Direct Air Capture (DAC)

Unlike many of the other CDR options discussed in this paper, DAC has fewer variables to consider when analyzing the sequestration potential. The carbon dioxide removal (CDR) potential of DAC is highly dependent on two factors. The capture system (solid or chemical sorbent) and the type of chemical sorbent used are the biggest factors. It is estimated that DAC has the potential to sequester and store between 0.0004 and 16 $GtCO_2$ annually. It is important to note that most of the estimates were based on a single DAC unit, only the highest two were based on total DAC activity for a given year. In the single unit cases, it was assumed that more than one unit would be operated in a year. We assumed that 1,000 such units would operate in a year for the purpose of extrapolating the potential CDR rate. Compared to Lackner's assertion that the units would not be more complicated than a car to mass produce and between 1 and 10 million solid sorbent DAC units could be produced annually (Lackner et al, 2010; Lackner et al., 2012), 1,000 units is conservative. This paper does not evaluate the sequestration estimates after multiple years of producing DAC units. However, the American Physical Society report indicated that building 80 DAC systems having the design they analyzed would remove an average of 4 $GtCO_2$/yr over 100 years (Socolow et al., 2011). The CDR potential of DAC is listed by source in Figure 7-2.

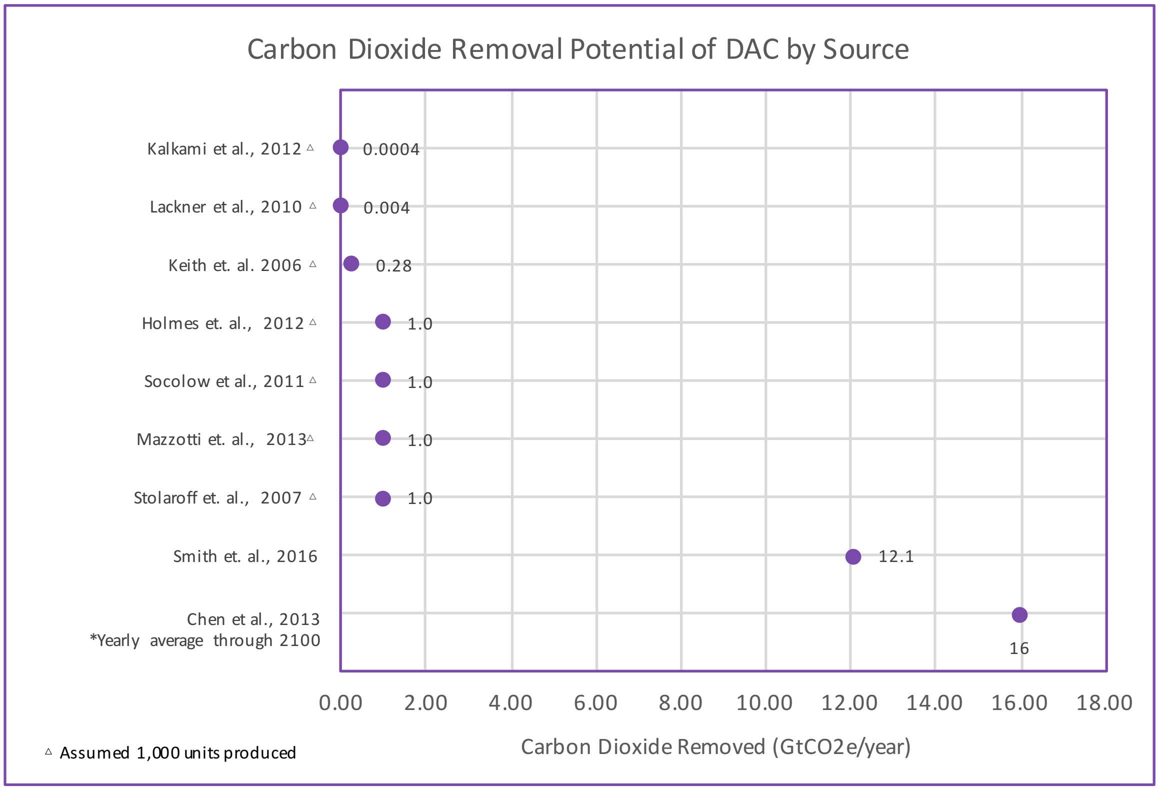

Figure 7-2: Graph of Carbon Dioxide Removal Potential in Gt of carbon dioxide equivalency per year of DAC.

The sequestration estimates for DAC differ from the other CDR options mentioned because the DAC system is humanmade and sequestration amounts can be manipulated, rather than dictated by naturally occurring limits. Many researchers have indicated the sequestration rate of a unit should be 1 $MtCO_2$/yr to make a measurable difference at the atmospheric level (Holmes et al., 2012; Mazzotti et al., 2013; Socolow et al., 2011; Stolaroff et al., 2008). While these hypothetical DAC units may capture the equivalent amount of CO_2, they vary in design. All four of these systems use an aqueous NaOH solution to capture CO_2. Socolow (2011), Holmes (2012) and Mazzotti (2013) assume a traditional contactor design. However, Stolaroff (2008) assumes a spraying mechanism to capture CO_2. That design is described as an airport hangar style structure used to support the spraying apparatus (Stoloroff et al., 2008). On the low end of the sequestration range, the design of the systems differ. Kulkarni (2012) assumes an amino-modified silica adsorbent and Lackner (2010) uses a design that mimics a furnace filter with thin anion exchange resins that create a panel for CO_2

to adhere. Keith (2006) discusses the NaOH aqueous sorbent with a spray tower design and limits the amount of CO_2 capture to 76,000 tC/yr based on parameters of the spray tower. While this design is similar to Stoloroff's (2008), the dimensions of the structure vary; Stoloroff's (2008) dimensions are 760 m by 760 m by 20 m high while Keith's (2006) has a diameter of 110 m and is 120 m high.

While the low and medium range estimates are centered around current ability to sequester CO_2, the high end of the sequestration potential estimates are based on estimates for the year 2100. Smith (2016) indicated that BECCS (discussed in Chapter 8) had a potential of 12.1 t/CO_2/yr by 2100 and indicated that there was no barrier for an engineered chemical reaction DAC system to meet that same level of sequestration. Chen (2013) estimated total carbon sequestration potential through 2100 based off 1 MtCO_2/yr DAC units at 489 GtCO_2 and an annual rate of 16 GtCO_2 based on similar technology to the APS study.

Due to the APS DAC system's prevalence throughout the reviewed literature and subsequent academic work to optimize specific aspects of this DAC deign, a removal potential of 1 GtCO_2 was selected for comparative purposes with other CDR options. It is important to note, this number is highly dependent on the number of units in operation.

Economic Analysis of Direct Air Capture (DAC)

DAC is still in the early stages of development and this can be seen in the range of the estimated costs for sequestering one tonne of CO_2. The range between the estimates is the largest of any of the CDR options. The cost of DAC ranges from \$30 to \$1,050/tCO_2. Estimated financial costs of DAC are listed by source in Figure 7-3.

The low end of the range includes Lackner's (2010) estimate of \$30/tCO_2, this estimate is for solid sorbents and is a cost in the unspecified future. The current cost for Lackner's design is \$218/tCO_2 and this is still on the low side of the range. The other solid adsorbent is proposed by Kulkarni (2012) and is an amine-functionalized silica which couples with temperature swing adsorption. This design is also at the low end of the cost range at \$98/tCO_2. The solid sorbent design uses less energy due to the elimination of the energy intensive step of sorbent regeneration. This allows lower cost estimates than other designs (Kulkarni et al., 2012).

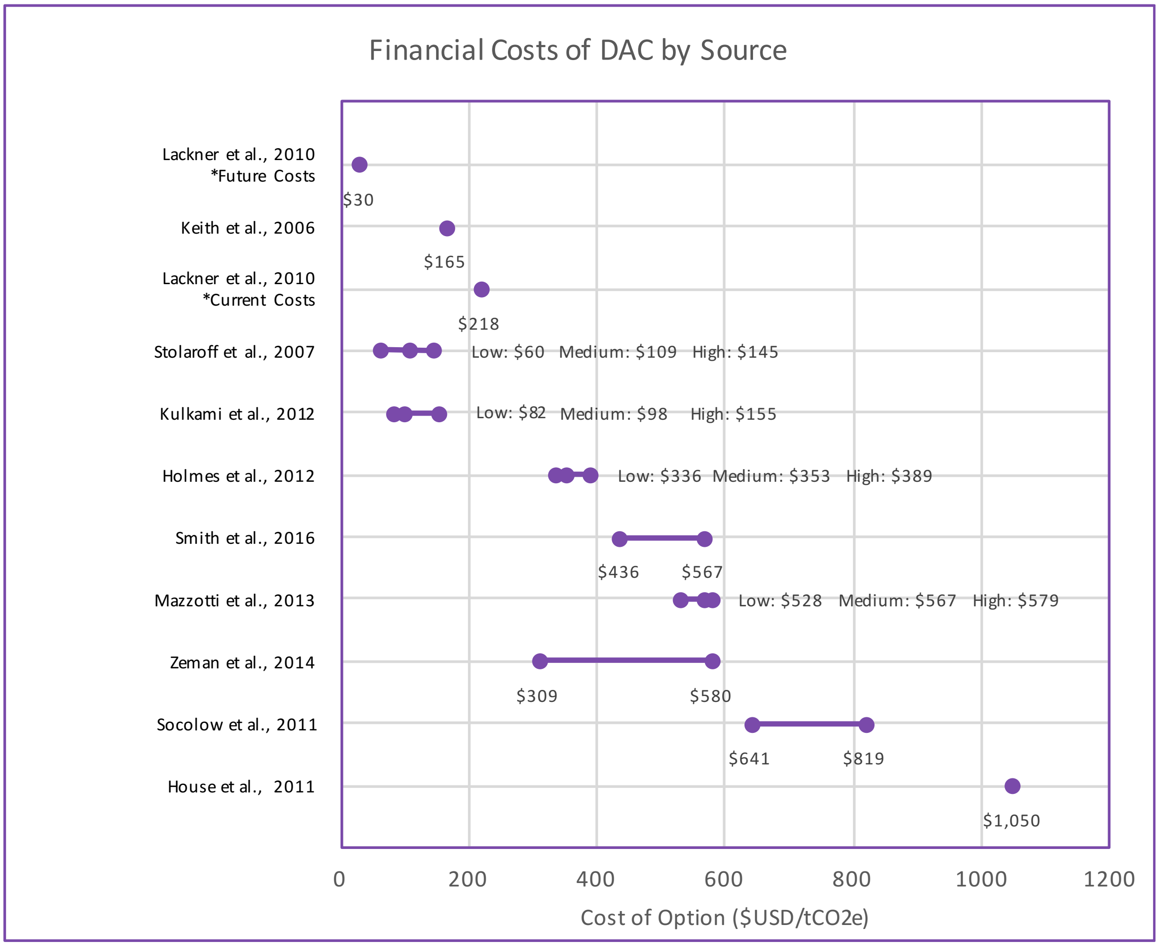

Figure 7-3: Graph of financial costs of DAC in 2015 US Dollars per tonne of carbon dioxide equivalency.

The rest of the cost estimates are based on aqueous chemical capture designs. The range in this group is still almost as large as the entire range, from $60 to $1,050/tCO$_2$. The major differences causing this spread are the components covered in the estimate and the design or specifications of the system. Stoloroff (2008) and Keith (2006) have the lowest estimates in this range and both use a version of a NaOH spray to capture CO$_2$, while the other estimates are based off a contactor with NaOH inside. Stoloroff (2008) does not include solution recovery or CO$_2$ sequestration costs in their estimate. David Keith is the first person to give a rough cost estimation of a DAC system using sodium/calcium hydroxide sorbent. Keith's (2006) estimate of $165/tCO$_2$ is for a complete system, excluding storage costs. This estimate is built on components found in industry today but also assumes "significant" research and development for construction. This design uses lower amounts of energy for calcination and compression (Keith et al., 2006); this could explain why this estimate is lower than others.

The American Physical Society report on DAC and the system that was discussed became the starting point for several of the midrange cost estimates. The CO_2 capture steps discussed in the carbon sequestration section of this chapter discussed the APS design of NaOH and calcinator cycling system. The low end of their estimate was for optimistic costs while the high end was what they thought were more realistic costs for their system. The estimate did not include storage costs (Socolow et al., 2011). Holmes (2012), Mazzotti (2013), and Zeman (2014) all use the APS design as a base for their analysis. Holmes (2012) redesigned the shell and packing materials of the contactor and found that their design reduced the cost of the contactor process by four-fold. All other cost components were used from the APS report (Holmes et al., 2012). Mazzotti (2013) used the APS design and cost estimates but optimized the air velocity, liquid velocity, and recovery which resulted in a lower cost estimate than the APS report (Mazzotti et al., 2013). Zeman (2014) reconfigured the packing in the contactor to reduce electricity and uses different energy sources to run the system which resulted in lower costs.

The highest estimate of DAC is from House et al., 2011. This number has been cited as a reason to forego DAC due to its exorbitant cost while others argue the estimate itself is unrealistic. The biggest reason for the difference between House's estimate and others is that it is based on existing trace gas removal systems, thermodynamic efficiencies, and the Sherwood Plot to describe how costs rise with lower concentrations of a diffuse gas rather than a specific DAC system (House et al., 2011). Critics have stated that specific DAC designed systems are a better representation of actual costs (Smith et al., 2016). Another difference between House et al. (2011) and the majority of the estimates is the capture rate. House uses a capture rate of 90% while most other studies used a capture rate of 50%, (Holmes et al., 2012; House et al., 2011; Mazzotti et al., 2013; Socolow et al., 2011; Zeman, 2014).

As can be seen in Figure 7-3 there is significant variation between the estimates from the studies. Due to this variation, descriptive statistics were employed to create a quartile analysis. Using this analysis, 50% of the estimates suggest that the cost of capturing and storing 1 tonne of CO_2 is between \$147 – \$567/tCO_2 with a median figure of \$345/tCO_2. The quartile analysis is graphically depicted in a box-and-whisker graph in Figure 7-4.

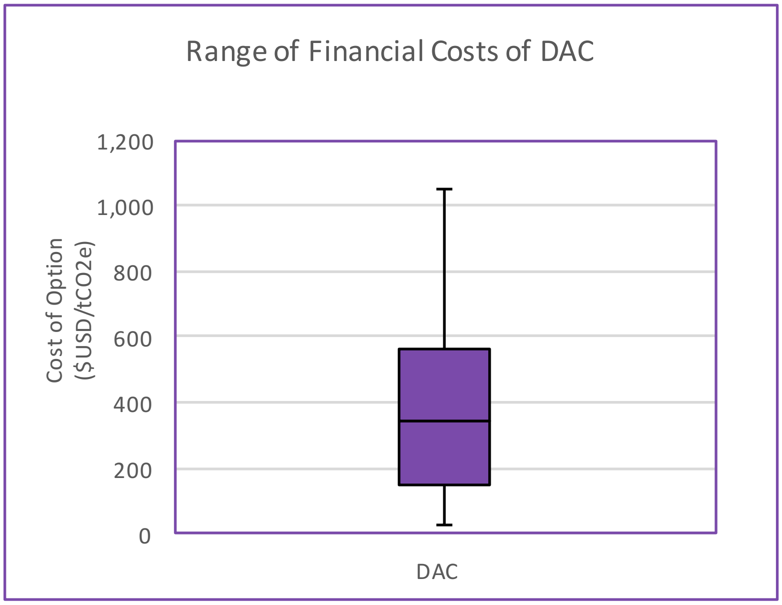

Figure 7-4: Graph of range of financial costs of DAC in 2015 US Dollars per tonne of carbon dioxide equivalency. Min: 30; 1st: 147; Median: 345; 3rd: 567; Max: 1,050 USD/tCO_2$e.

Geographic Restrictions

One of the most promising aspects of DAC systems is their lack of ties to any specific geography, region, or emissions source (Chen et al., 2013). These systems can technically be placed anywhere as long as there is available energy to power the system. Since a DAC system can be located almost anywhere, they can be placed in locations that would be ideal for storage (Keith et al., 2006; Lu et al., 2013) or utilization facilities. Even though DAC systems requires significantly less land than other CDR options, the systems can get very large and society may deem them as an eyesore so they should be placed away from population centers. For example, to offset a 1,000 MW coal power plant, roughly 6 MtCO$_2$ annually, a DAC system would need to the 10 meters high and stretch 30 km (Socolow et al., 2011). While there are no distinct limitations, there could be performance differences between DAC systems in different regions due to humidity and temperature (Socolow et al., 2011).

Policy Implication

Implementing DAC provides more leeway for society to better adjust to combatting climate change. It allows societies the flexibility to still use fossil fuels in a limited capacity for industries or activities that are challenging to de-carbonize, like airplanes. DAC's ability to be sited in most locales with a significantly lower geographic footprint than other CDR options opens more policy options when addressing climate change. As DAC removes carbon directly from the atmosphere, there may be questions about what countries should build these systems and how many. There could be conflicts if countries feel like they are cleaning up the carbon of other countries who have not built DAC systems or have not built enough to cover their emissions. Even if a country sufficiently covers their emissions, there is a question about who pays for these systems if their costs prohibit them from being commercially viable. As mentioned in the geographic restriction section, some of these systems can be large and may be considered an eyesore; there may be conflicts with the siting of these systems if they are too close to residential areas.

Benefits, Challenges, and Tradeoffs

The benefits of a DAC system are numerous. Besides energy, DAC is independent of large-scale inputs for operation, like biomass for BECCS and Biochar, iron for ocean fertilization, or minerals for accelerated weathering. Depending on the system, the amount of land these systems require may be less than other CDR options. While the APS report indicates a 30 km long structure, Lackner (2010) envisions a DAC system the size of a shipping container. Stoloroff's (2008) and Keith's (2006) DAC systems fall between these two extremes, whose dimensions were discussed in the removal potential section. A smaller geographic footprint would reduce land use competition and indirect land use issues that other CDR options must contend with. Lackner (2010) estimated that his design, the size of a shipping container, equals a hectare of biomass (Lackner et al., 2010). When other CDR options are faced with land limitations, DAC can assist with making up the shortfall. DAC systems can be constructed near geologic storage sites which reduces transportation infrastructure and costs (Lu et al., 2013). Additionally, the use of DAC in the latter part of the century allows for an overshoot of GHG emissions and prolongs the use of fossil fuels to allow an easier transition to a de-carbonized economy (Chen et al., 2013).

The challenges to DAC are just as big as the benefits of successful implementation. The expense of DAC is one of the largest challenges. Even at the median cost of $\$345/tCO_2e$ it is not a financially viable option. This level of costs will not be justifiable from an economic perspective and DAC will not be implemented, much less researched, if the economics of a commercially scalable system are not feasible.

A large portion of these costs come from the energy requirements to operate DAC systems (Socolow et al., 2011). A recent study in the Journal of Modern Power Systems found that DAC costs could be reduced by \$6 to \$167/tCO_2 when using wind power to operate a DAC system (Yinghui et al., 2016). The energy requirements of a DAC system come from 3 main areas: pushing ambient air through the DAC system, regenerating the sorbent, and transporting captured CO_2 to its final destination (Keith et al., 2006). The total estimated energy requirement for DAC is 156 EJ/yr (Smith et al., 2016). Using remote fossil fuel energy to operate the DAC system produces 300 kg CO_2 per tonne of CO_2 captured so the energy must come from non-carbon emitting sources or the negative emissions of the DAC system are reduced or eliminated (Socolow et al., 2011). Solid sorbents have a smaller carbon penalty than aqueous solutions as they use less energy overall (Lu et al., 2013). Due to the energy requirements, reducing CO_2 emissions from power plants, industrial processes, and other point sources is the first step in keeping our planet below 2° C warming (Friedlingstein et al., 2014). This is a challenging feat, however, many of the studies in this paper assume that this is possible. Thus far, the trend towards decarbonization has not occurred fast enough. Before renewable power can power DAC systems, it must first offset fossil fuel generated electricity (Chen et al., 2013; Mazzotti et al., 2013; Smith et al., 2016).

While energy consumption is a challenge for DAC, water consumption is also a concern. This concern should be addressed while siting DAC systems to ensure that adequate water supplies are present and do not compete with local drinking and irrigation water needs. The mean water use to capture a tonne of CO_2 is roughly 25 m^3, totaling 300 km^3 annually (Smith et al., 2016). There is a consensus that DAC will not be a viable option until mid-century (Chen et al., 2013). This makes modeling and estimating the role of DAC uncertain and further skews the understanding of DAC's potential. DAC has been referred to as a possibility for 2050 and beyond (Chen et al., 2013; Smith et al., 2016).

Future Research

There are currently pilot projects underway from companies such as Carbon Engineering, Infinitree, Skytree, and Climeworks (Carbon Engineering, 2017; Climeworks, 2017; Infinitree, 2017; Skytree, 2017). A team from UC-Berkley synthesized a new material with larger capacity, higher selectivity, and quicker absorbing of CO_2 from dry gas mixtures with N_2 and O_2. Their future work will largely rely on determining the potential for CO_2 capture from ambient air (McDonald et al., 2012).

Further research is needed to find more efficient ways to collect CO_2 from the atmosphere. This includes refinement of many of the components of the DAC system. The size of the contactor which administers the sorbent and CO_2 bond is limited by size. The capture rate 20 $tCO_2/yr/m^2$ is a limiting factor in CO_2 capture (Socolow et al., 2011). Increasing the performance of the contactor is possible with a new chemical sorbent that strongly attracts CO_2 and subsequently can separate those chemical bonds with minimal energy. Forcing the air through the contactor is also an area of focus to improve performance and lower energy consumption (Socolow et al., 2011). Further design work should focus on the materials used in the shell and packing of the DAC system as seen in the four-fold reduction in costs by Holmes (Holmes et al., 2012). This will reduce the costs and energy of making the components of the system. Most of the academic work is based on models and future assumptions; more information is needed to better predict DAC's role in reducing CO_2 since academic costs tend to be lower than industry costs (Socolow et al., 2011).

Conclusion

Direct air capture holds the promise of capturing CO_2 from the ambient air. It can collect CO_2 beyond a point source and isn't dependent on a biological process. It is able to capture CO_2 in most locations and can be sited in places that are out of the way or close to a storage site. DAC is a speculative option. It cannot be commercially scaled until mid-century and that assumes an excess of carbon-free energy will be available to power these energy intensive units. The high costs, ranging from \$30 to \$1,050/tCO_2 leave the future of DAC uncertain. The cost per tonne of CO_2 must drop for DAC to be economically viable in the future. This will entail significant research to create new sorbents which easily bind CO_2 but can also break those bonds with low energy costs. The potential CO_2 sequestration in DAC is determined by how many DAC units are produced and operating so while this paper has a range of 0.0004 – 16 GtCO_2 sequestration potential yearly, it will be determined by the production levels of future DAC systems. Whatever DAC's potential, it should not be relied upon as a savior in several decades, curbing emissions and de-carbonizing the energy market should be accomplished regardless of DAC's future role.

Chapter 8:

Terrestrial Bioenergy with Carbon Capture and Storage (BECCS)

Terrestrial Bioenergy with Carbon Capture and Storage (BECCS)

Introduction

Key Findings

- *BECCS is considered a demonstrated CDR option due to the prior work done on bioenergy and carbon capture and storage (CCS).*
- *BECCS has the potential to capture 9.2 $GtCO_2e$/year at an approximate price of \$61/tCO_2e.*
- *However, when all current literature is considered, the estimates range between 0.04 – 32.1 $GtCO_2e$/year at a cost between \$21 - \$436/tCO_2e.*

One of the most widely assumed carbon dioxide removal (CDR) options is terrestrial bioenergy with carbon capture and storage (BECCS) (Creutzig et al., 2014). BECCS is the process of capturing carbon dioxide (CO_2), which accumulated in biomass while the vegetation was growing, through creating an energy product. The two main energy products are electricity and biofuels. Bioenergy forms the foundation for BECCS. Bioenergy, referring to energy derived from recently living (as opposed to fossil) biomass, accounts for 56 EJ of primary energy per year (World Energy Council, 2016). This is roughly 10% of total global primary energy use. The markets include domestic heat, large-scale industrial and community combined heat and power plants, and co-firing plants with coal (Bauen et al., 2009). Primary bioenergy use is expected to rise 25% - 33% to 200 – 500 EJ per year by 2050 (Bauen et al., 2009). BECCS takes bioenergy a step further by capturing carbon from the facilities which make electricity and biofuels. The CO_2 emissions created from these energy products is captured before re-entering the atmosphere thus creating negative emissions. Currently, there are 15 pilot BECCS plants in the world (Gough et al., 2015). BECCS is a key component of the integrated assessment models (IAMs) and it is projected that mitigation costs would be twice as high without BECCS (Kriegler et al., 2013).

The Terrestrial BECCS Process

The BECCS process starts with biomass and the associated harvest for bioenergy production purposes. The transport, storage, and handling of biomass can be a challenge due to the cost, volume, and low energy content of unprocessed biomass. Pelletization, pyrolysis, and torrefaction are all options to overcome these challenges (Basu, 2013). Pelletization compresses biomass and creates pellets which are easy to transport. These are most commonly used in the industrializing world and are made from sawdust. During transport, however, they have a propensity to absorb moisture. In addition to easing transport, pellets create dense forms of biomass which are essential for large-scale biomass use since biomass is five times less dense than fossil fuels. Pyrolysis uses thermal decomposition with the absence of oxygen and creates bio-oil, syngas, and biochar (see Chapter 5 for more information on biochar). Over time these products degrade. Therefore, long term storage is not optimal. Another approach, torrefaction, uses a high-efficiency thermal process to create a coal-like product that can be made into pellets (Basu, 2013).

The main technologies used to convert biomass to heat and power include combustion, gasification, co-firing with fossil fuels, and anaerobic digestion (Bauen et al., 2009). Biomass can come in the form of energy crops, perennial plants, crop residues, harvested wood, forest residues, and municipal and industrial waste (Tilman et al., 2006). Generating heat from biomass is the traditional use of biomass. Electricity is produced through combustion, gasification, combined heat and power (CHP), municipal solid waste, and co-firing with fossil fuels. The energy yield is based off what kind of energy crop is used (Berndes et al., 2003).

Beyond electricity generation, biofuels are another way to produce energy from biomass. Depending on the geographic region, countries use different crops to produce biofuels. In the US, most of the biofuel is derived from corn in the form of ethanol, while Brazil depends on sugarcane. Combined these two countries produce 70% of all biofuel (Myers, 2015). First generation biofuels are an established technology and include biodiesel, bioethanol, and biomethane. Second generation biofuels rely on different feedstocks to produce bioenergy. They focus on cellulosic crops. These crops have more embedded energy than first generation crops and can be grown on a wider range of land types (Heaton et al., 2008, McLaughlin et al., 1998). While Bauen (2009) expects these fuels will become commercially viable in a decade, Sims (2013) states there are major obstacles to overcome in breaking down these resources before they are commercially viable. Biofuels, other than the long-established first-generation options derived from sugars and lipids, have been in development for four decades and are still not commercially viable (Sims, 2013) therefore, commercial scale production of these fuels is unlikely in the near future.

BECCS takes bioenergy a step further by capturing carbon from facilities which make electricity and biofuels. The sequestration of CO_2 at a bioenergy production facility becomes synonymous with carbon capture and storage (CCS) at fossil fuel power plants. The concentrated stream of CO_2 emissions produced at these facilities is easier to capture than the diffused CO_2 in the air before it was captured by the biomass. The captured CO_2 can subsequently be used as an input into another industry or permanently stored in geologic formations (Williamson et al., 2016).

The focus of CCS has been primarily on coal due to its larger emission intensity than other fossil fuels (EIA, 2016). Co-firing of biomass with coal can transform CCS into BECCS. The following steps to capture CO_2 relate to CCS but are readily transferable to BECCS. The first step to capture and store CO_2 is to create a dense CO_2 stream. This can be done in 3 ways, pre-combustion, post-combustion, or oxyfuel combustion. Pre-combustion involves integrated gasification combined cycle (IGCC) plants; natural gas combined cycle are primarily used with post-combustion. In the pre-combustion approach, air enters an air separation unit which separates oxygen from nitrogen. The oxygen is sent to a gasifier where it is combined with fuel. This new gas is then combined with steam to separate hydrogen and CO_2. The hydrogen becomes an input for fuels and is sent to a gas turbine to produce electricity. The CO_2 is compressed and dehydrated to prepare it for transport and storage (Benson et al., 2012).

More interest has been shown in post-combustion in recent years compared to pre-combustion (Benson et al., 2012). Post-combustion involves air and fuel entering a boiler to produce steam, CO_2, nitrogen, and water. The steam is diverted to a turbine to produce electricity and a portion is sent with the other byproducts to a chemical wash. In the wash, the CO_2 is stripped from the nitrogen and water. This reaction is simpler than the chemical processes in pre-combustion. The CO_2 is then compressed and dehydrated to become transport ready. Lastly, the oxyfuel combustion cycle uses the air separation unit from the pre-combustion approach but sends oxygen to a boiler to be

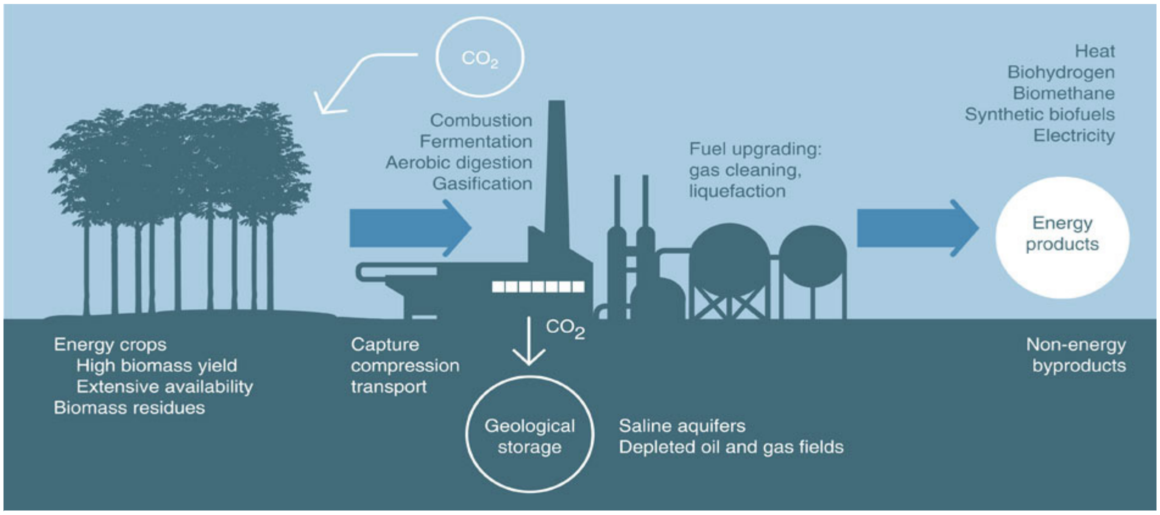

Figure 8-1: Diagram of BECCS process. Image from Canadell & Schulze, 2014.

combusted with the fuel. Like the post-combustion approach, the output steam is sent to a turbine to create electricity, however, some of the CO_2 and water is recirculated to the boiler to control the temperature, and the rest is compressed and dehydrated to be prepared for transport and storage (Benson et al., 2012).

On the other hand, biofuels are produced with energy crops, industrial and municipal wastes, and forestry residues (Bauen et al., 2009). Currently, biomass dedicated to biofuel production are from first-generation energy crops--maize in the United States, sugarcane in Brazil, and wheat in the United Kingdom (Bauen et al., 2009). Biofuels are not inherently carbon negative and can be neutral or net positive depending on the biomass, the inputs into the production of the biomass and biofuel, and the transportation associated with it (Bauen et al., 2009). Biofuels can be carbon negative when low input, high-density grasslands are used with minimal biomass production inputs (Tilman et al., 2006). The above ground biomass is harvested and the biomass, in its entirety, is processed for fuel, unlike current maize or sugarcane-based ethanol (Tilman et al., 2016). CO_2 is also captured through the production of biofuels by capturing CO_2 during the fermentation process (Rochedo et al., 2016).

The Terrestrial BECCS Process

The overall process would consist of the following steps:

1. Harvest of biomass, in the form of energy crops, biomass residues or wastes.
2. Conversion of biomass into energy dense fuel products.
3. Transport biomass fuel products to energy producing facility.
4. Capturing CO_2 to avoid its release from biomass combustion for energy production.
5. Captured CO_2 is transported to saline aquifers or depleted oil and gas fields.
6. Sequestration of the CO_2.

Carbon Dioxide Removal Potential of Terrestrial Bioenergy with Carbon Capture and Storage (BECCS)

The CDR potential of BECCS is highly dependent on a multitude of factors. The kind of biomass used (i.e. species of biomass, forest residues, wastes) determines the energy content and carbon uptake of the biomass (Clark et al., 2011; Wiltshire et al., 2015). The available biomass is highly dependent on the geographic location of these activities. The land management practices of biomass growth and method of production for an energy product determines how much CO_2 is emitted (Bauen et al., 2009). How far the biomass travels to the processing plant and how far the captured CO_2 travels to its final storage location determines how much CO_2 is emitted during the transportation stage. These factors combined to constitute the net emissions of BECCS.

Based on the academic literature, which varies by region evaluated, the scale of the BECCS program, energy product produced, the method of production, the biomass used, and the model utilized, it is estimated that BECCS has the potential to sequester and store between 0.06 – 32.1 $GtCO_2e$/yr. The CDR potential of BECCS is listed by source in Figure 8-2.

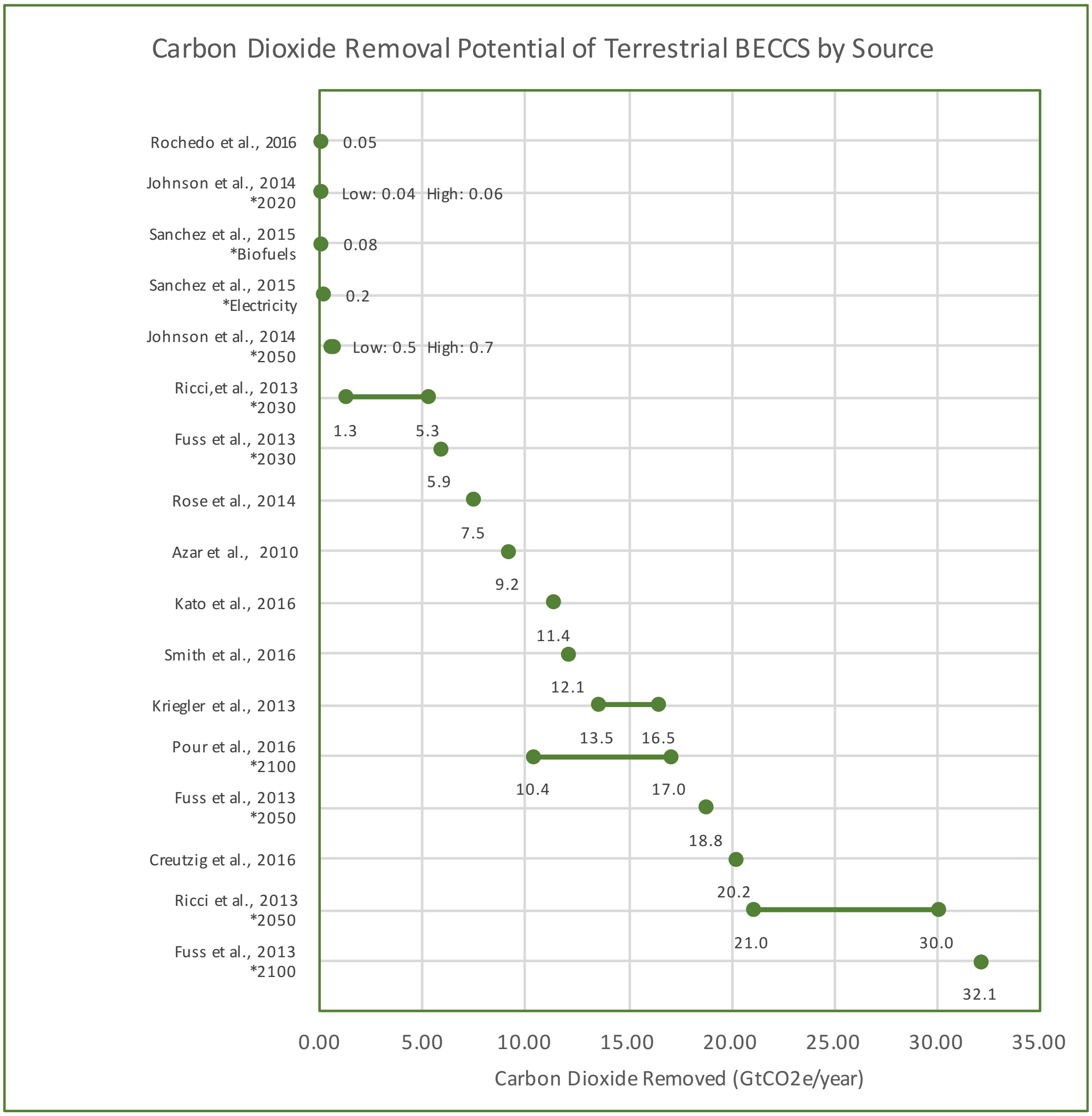

Figure 8-2: Graph of Carbon Dioxide Removal Potential in Gt of carbon dioxide equivalency per year of BECCS.

The largest reason for the range of values between the literature is the scope of the project, the time of the estimate, and the amount of bioenergy that is available to be produced. For example, Rechedo (2016) references BECCS activities in Brazil for 2030, Sanchez (2015) references BECCS activities for Western North America for 2015, and Johnson (2014) looks at the impact of US biofuels negative emissions potential. Johnson (2014) optimizes sequestration potential on US biofuel demand from IEA 2012 figures. As the number of years to which the estimates apply increase, the amount of sequestration potential trends upwards. Ricci et al.'s 2013 estimate of 1.3 - 5.3 $GtCO_2$/yr in 2020 and 21-30 $GtCO_2$/yr in 2050 are based on world averages and used the TIAM-FR optimization model which is driven by end use demand at minimum global costs. The middle of the range includes Azar, (2010) which estimated sequestration potential at 9.2 $GtCO_2$/yr (converted from 2.5 GtC/yr) to produce 100 EJ/yr between 2050 and 2100. It assumes the use of 500 million hectares and an average yield of 10 t of dry mass per hectare (Azar et al., 2010). The highest estimates belong to Fuss (2013) at an estimated sequestration potential of 5.85 $GtCO_2$/yr in 2030, 18.8 $GtCO_2$/yr in 2050 and 32.1 $GtCO_2$/yr in 2100. Fuss (2013) uses 41 EJ for 2030, 132 EJ for 2050 and 225 EJ for 2100 and assumes that the biomass will be fully exploited in electricity generation. Ricci (2013), on the other hand, assumed 2050 bioenergy at 234 EJ, 72 EJ resulting from bioenergy crops, 72 EJ from solid biomass resources and the remaining from industrial and municipal wastes and landfill gas. The models used to create the sequestration potential varied between studies and the different underlying assumptions and drivers of the models contributed to the different estimates. Azar (2010) used IMAGE/TIMER, GET and MESSAGE, Ricci (2013) used TIAM-FR, Kriegler (2013) used REMIND, and Fuss (2013) used a styled model to find an optimal mitigation strategy considering negative emission options, CO_2 sinks, and uncertainty.

As can be seen in Figure 8-2 there is significant variation between the estimates from the studies. Due to this variation, descriptive statistics were employed to create a quartile analysis. Using this analysis, 50% of the estimates suggest that BECCS could sequester and store between 0.6 – 16.8 $GtCO_2e$/yr with a median figure of 9.2 $GtCO_2e$/yr. The quartile analysis is graphically depicted in Figure 8-3.

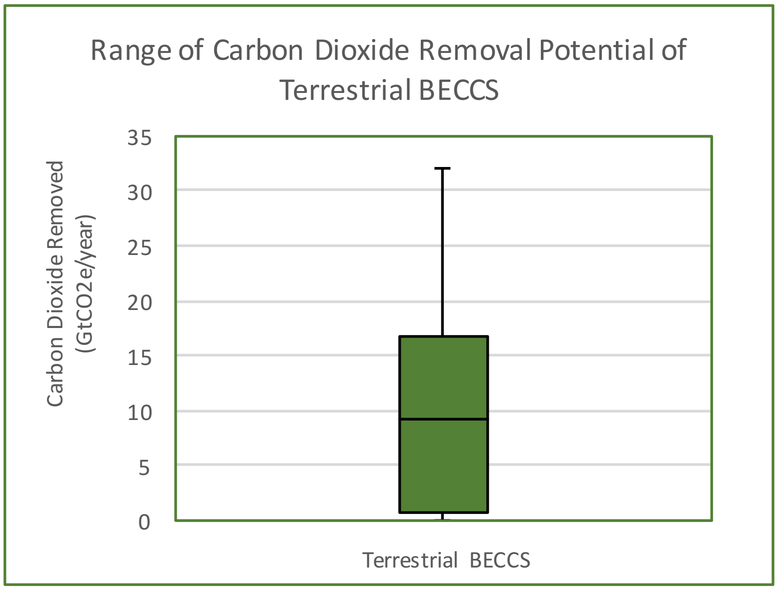

Figure 8-3: Graph of range of carbon dioxide removal potential in Gt of carbon dioxide equivalency per year of BECCS. Min: 0.04; 1st: 0.6; Median: 9.2; 3rd: 16.8; Max: 32.1 $GtCO_2e$/year.

Economic Analysis of Terrestrial Bioenergy with Carbon Capture and Storage (BECCS)

The relatively low cost of BECCS makes it an attractive mitigation tool, especially compared to other CDR options such as DAC. The costs for BECCS increase as the amount of carbon sequestered increases, especially when sequestration rates surpass 12 $GtCO_2$/yr (Kriegler et al., 2013). This is mainly due to increased competition for land and additional infrastructure needed to produce sufficient biomass and transport such large amounts of CO_2 (Mollersten et al., 2003). The range of cost estimates is between \$21 - \$436/tCO_2e. Estimated financial costs of BECCS are listed by source in Figure 8-4.

The economic differences are explained by the differences in electricity generation and biofuels, cost calculation formula used, the activities included in the cost estimates, and underlying cost assumptions. The actual costs of biofuel or electricity generation will vary significantly due to the market price of biomass feedstocks at any given time. This is expected to vary regionally based on what biomass can be grown in the area and the local yields. Assumptions were used to estimate the yield rates used to run the models. For example, Azar (2010) assumes annually 10 tonnes of dry matter can be harvested per hectare (Azar et al., 2010) while Ranjan (2010) assumed 12 tonnes of dry matter and Creutzig (2014) assumed 40 tonnes of dry matter.

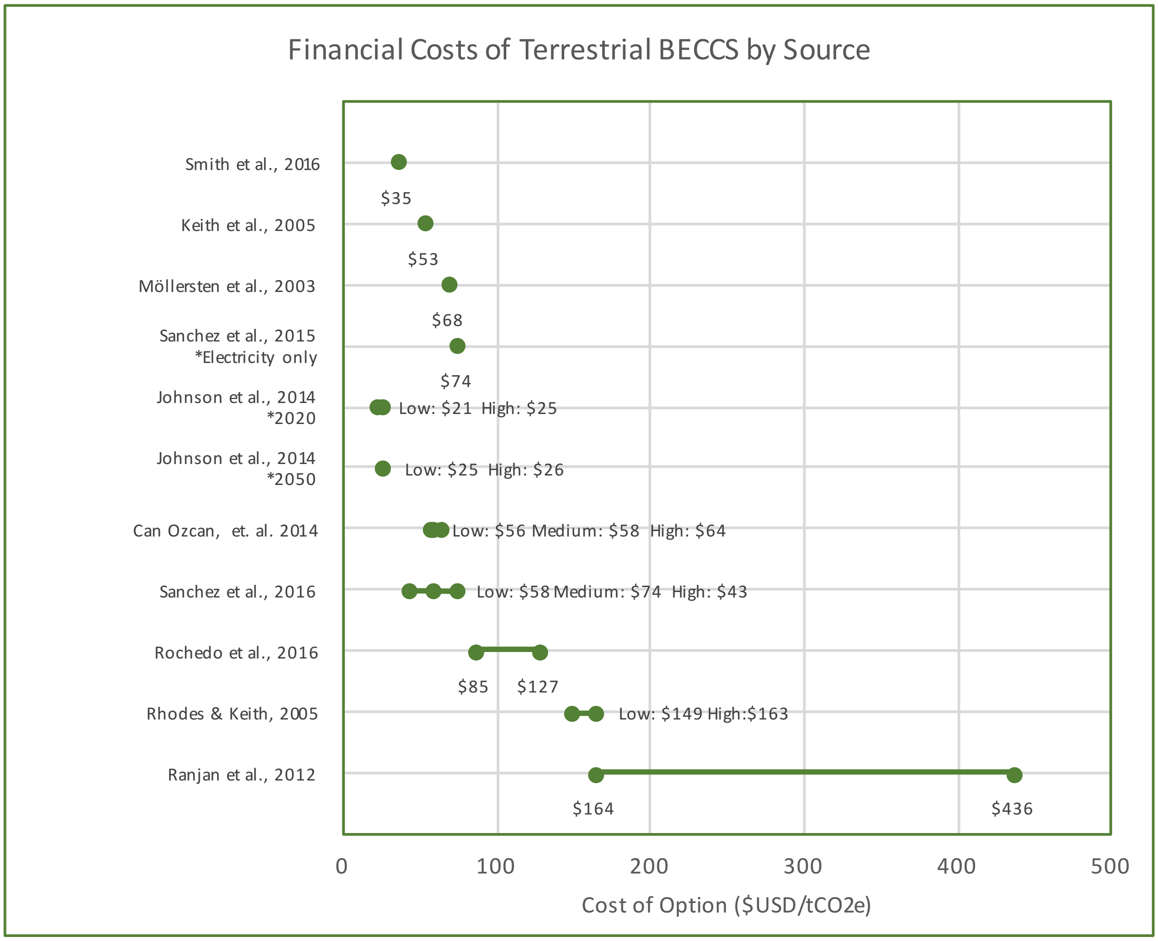

Figure 8-4: Graph of financial costs of BECCS in 2015 US Dollars per tonne of carbon dioxide equivalency.

There are two energy products discussed throughout the literature, electricity and biofuels. Each has their own processes of energy generation and CO_2 capture and subsequently have their own cost estimates. Electricity generation encompasses the entire range of the estimates from $21 - $436/t$CO_2$. Biofuels cost estimate range falls between the electricity range at $68 - $127/t$CO_2$. For the low end of biofuels, Möllersten (2003) reported only capital costs and lost energy production while the high end, Rochedo (2016) reported costs that included dehydration, compression, transport, and injection.

There are three commonly used cost calculations throughout the BECCS literature to present the cost per tonne of CO_2; captured cost, avoided cost, and abatement cost. The captured cost is calculated to provide the costs associated with capturing CO_2; the following formula shows the calculation:

$$\frac{(COE_{Capture} - COE_{Ref}) \times MWh_{Capture}}{CO_{2_{Capture}}}$$

For the purposes of this paper, abatement costs are synonymous with capture costs. This equation neglects to include the energy required to capture CO_2 so the additional CO_2 it takes to capture the CO_2 is not included in the estimate. The avoided costs formula accommodates for this by using the difference in intensity between non-capturing and capturing power plants. The formula is:

$$\frac{(COE_{Capture} - COE_{\mathrm{Ref}})}{(Intensity_{Ref} - Intensity_{Capture})}$$

This difference in calculations makes avoided costs higher than captured costs for the same scenario due to the reduced amount of CO_2 that is assigned to the costs. Ranjan (2010) and Can Ozcan (2014) reported avoided costs, Rochedo (2016) and Sanchez (2015 & 2016) reported abatement costs, and Smith (2016) reported captured costs. Biofuels do not appear to report cost estimates based on these calculations.

The steps of BECCS which have identifiable costs are capture-related, transport, and storage. The estimates vary in which costs are included in the estimate. Smith (2016) and Rochedo (2016) includes capture, transport, and storage costs, Johnson (2014) includes transportation costs with capture-related costs, and Keith (2006), Möllersten (2003), Sanchez (2015 & 2016), Can Ozcan (2014), Rhodes (2005), and Ranjan (2010) report only capture-related costs.

The different underlying cost assumptions used to create the estimates contribute greatly to the variance in estimates. The discount rate to determine the present value of future cash flows is 10% for Sanchez (2016) and Johnson (2014), Rochedo (2016) uses 8% and 15% for their low and high scenarios, and all others do not indicate a discount rate. Ranjan's (2010) estimated cost range is higher than the other estimates; this may be explained by the CO_2 capture rate used. Ranjan (2010) used a capture rate of 90% while Rhodes (2005) used capture rates of 44% and 55% for two different plant configurations and Johnson (2014) used 14% and 56% CO_2 capture rates for two different biofuel products. Sanchez (2015) used 85% capture efficiency and reported estimated costs up to \$74/tCO_2. This difference does not completely explain Ranjan's higher estimate.

Across the literature, there are many variables that are identified only in certain articles, so the comparison between all relevant variables is not possible. The following includes some examples of the identified variables. Keith (2006) uses a current electricity producer's cost of 3.5 cents/kWh to calculate near term costs. Möllersten (2003) assumes a 15% annual capital charge and assumes \$3/GJ for woody biofuels. Johnson (2014) used site-specific production costs and assumed cellulosic annual yield growth at 1%. Can Ozcan (2014) does not include drying costs in their estimate and assumes fixed operating costs at 3.7% of capital costs and variable operating costs at less than 1 cent/kWh. Sanchez (2016) used county level biomass supply data, transportation networks, existing technology cost estimates, and previous long-term geologic storage. Rochedo (2016) used averages and maximum values from peer reviewed literature for dehydration, compression, and storage coupled with fermentation specific capture conditions in the Integrated Environmental Control Model. Rhodes (2005) used a simplified engineering-economic model and their design assumes 10 years of "aggressive" research and development. Ranjan (2010) used 15.1% as the annual carrying charge. These assumptions do not correspond between papers and more than likely play a role in the differences in cost estimates but at this time are unable to be compared.

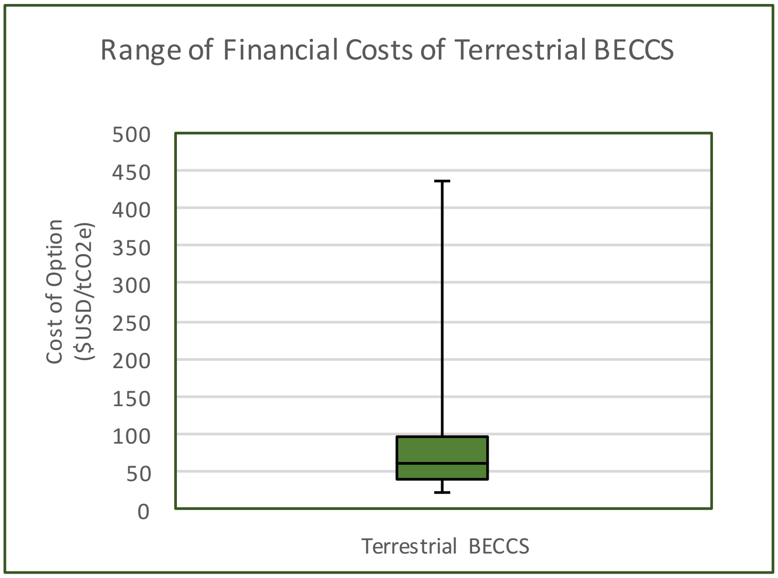

Figure 8-5: Graph of range of financial costs of BECCS in 2015 US Dollars per tonne of carbon dioxide equivalency. Min: 21; 1st: 41; Median: 61; 3rd: 96; Max: 436 \$USD/tCO_2e.

As can be seen in Figure 8-4 there is significant variation between the estimates from the studies. Due to this variation, descriptive statistics were employed to create a quartile analysis. Using this analysis, 50% of the estimates suggest the cost of sequestering and storing one tonne of CO_2 is between \$41 – \$96/tCO_2 with a median figure of \$61/tCO_2. The quartile analysis is graphically depicted in Figure 8-5.

Geographic Restrictions

BECCS is a geographically versatile CDR approach, except for areas with no vegetation. Energy crops can be grown on land suitable for agriculture. Abandoned and degraded agricultural land can be used to grow specific crops, such as perennial grasses (Campbell et al., 2008). Biomass can be harvested from forest and prairie ecosystems sustainably to produce biomass without the work required for energy crops (Tilman et al., 2006). Residue materials from forestry activities and industry can be used as a feedstock. Wastes from municipal or industrial activities can also be treated as biomass feedstocks (Berndes et al., 2003). While some crops may be suited to a particular area, each region has their own native or ideal biomass options to support BECCS.

Policy Implications

BECCS has received a great deal of attention because it has been assumed in numerous IAM scenarios designed for meeting a 2° C warming limit. This prominent role will make implementation of BECCS highly likely. The biggest hurdle regarding BECCS is the competition for land. If BECCS is to sequester any meaningful amount of CO_2 it will need a large amount of land to produce the needed biomass (Azar et al., 2010; Ranjan, 2010; Smith et al., 2016). This land will compete directly with agriculture, urban growth, and biodiversity. Some scientists envision that agricultural land will increase from 1.6 billion to 2.1 billion hectares by 2100, an estimated 83% of this increase would go towards bioenergy crops (Kato et al., 2014). The Food and Agriculture Organization estimates that food production needs to rise by 70% between 2005 and 2050 to meet growing demand (FAO, 2009). This scaling up of bioenergy crops, with or without BECCS, and food production shows the potential competition between bioenergy and other uses of ecologically productive land. Policies around this issue should include protections from food price increases, protection for agriculture lands, support of research and development to increase crop yields sustainably, protection of natural habitats and biodiversity, and promotion of mixed-use land use.

Further policy implications center upon indirect land use changes that can occur when agricultural land in one location is converted to another purpose and subsequently, new agricultural land develops elsewhere (Bauen et al., 2009), specifically by clearcutting tropical rainforests in South America. Land use change can create significant challenges on a policy level, but reducing the number of new farms which clear cut the rainforest would help mitigate indirect land use change. There is a potential for tension between markets when biomass can be treated as both a food crop and an energy crop. The value of this crop will most likely not be equivalent across the two markets and policies will need to be established to ease competition between the demand for biomass for BECCS and to feed the population (Bauen et al., 2009).

Benefits, Challenges, and Tradeoffs

As a prominent method to meet the 2° C target in most IAMs, it is unsurprising that BECCS has many benefits. One key benefit of BECCS is that it produces renewable energy. This provides an incentive to pursue CO_2 reduction strategies. However, the true value of BECCS still lies in its ability to sequester carbon from the atmosphere (Sanchez et al., 2015). In this light, BECCS accomplishes two goals, reducing CO_2 from the air and reducing new greenhouse gas emissions. Unlike other renewable sources of electricity, like solar and wind, BECCS can run continuously and provide a renewable baseload power generation option (Rowe et al., 2009). There is sufficient need for BECCS in the future. Low carbon energy provides 15% of current energy, including hydro and nuclear, this percentage needs to ramp up to 30% by 2030, 60% by 2050 and reach 90-95% by 2100 to meet long-term climate goals (Riahi et al., 2015). Creating the biomass necessary to meet the requirements of base-load power would entail a significant ramp up in energy crop production. This would have the economic benefit of creating jobs in rural areas and boost those economies (Rosegrant et al., 2008).

The technologies behind BECCS currently exist. While biomass provides 10% of primary energy (World Energy Council, 2016), there are around a dozen pilot projects of BECCS (Harvey, 2016). This small amount of implementation is indicative of the obstacles to overcome before BECCS is widespread. The biggest challenge for BECCS is the geographic scale which must be used to have a measurable effect on climate change (Kato et al., 2014; Wiltshire et al., 2015). For example, 180,000 square miles is needed to capture 1 $GtCO_2$ (House et al., 2011). Even using abandoned agricultural land, estimated at 385-472 million hectares (Campbell et al., 2008), the needed land mass will lead to competition with the agriculture sector. In 2015, 90 million acres of corn was grown in the US

(USDA, 2017), of this, 33 million acres will be turned into ethanol (Sands et al., 2017). To capture 12.1 $GtCO_2$, a land area equal to up to 25% of agricultural land and up to 46% of arable land is needed (Smith et al., 2016).

Rising food prices due to land use change is a major concern for BECCS (Wise et al., 2009). The FAO has reported that biofuels increase fuel insecurity (Gerbens-Leenes et al., 2009). Between 2002 and 2008, 75% of the increase in food prices is attributable to biofuels (Gerbens-Leenes et al., 2009). If BECCS competes with crop production, the caloric intake in North Africa, sub-Saharan Africa, the Middle East, Caribbean, and Latin America will decrease (Rosegrant et al., 2008). On the other hand, Babcock (2012) found that biofuel production did have a role in the increase of commodity prices but did not find that the 2008 increase in food prices were largely attributable to biofuel production. Instead, he indicated market-driven demand, subsidies, and tax changes played a larger role in food price fluctuations (Babcock et al., 2012).

Land use change to favor bioenergy crops is particularly worrisome in regards to the impacts of indirect land use change. As agricultural lands are converted to energy crop production, there will be a greater need for more agricultural lands in other regions (Ahlgren & Di Lucia, 2014). This can lead to the clearing of forests and other unmanaged land for agricultural use. The carbon emissions from deforestation are large and this leads to a net gain of CO_2 in the atmosphere instead of the negative emissions that are sought (Williamson et al., 2016). Using post-agricultural land for energy crops produces carbon emissions which are recouped in one year. Depending on the harvesting frequency of forest roundwood, the recoup time varies from 1 to 1,000 years (Mitchell et al., 2012). If tropical peat lands are deforested, it could take 1,000 years to recoup the carbon that was emitted during deforestation (Wiltshire et al., 2015). Clearing tropical rainforest contributes 12% to annual carbon emissions (Foley et al., 2011). Like land use change, there is the concern of biodiversity loss, especially if a monoculture energy crop is grown (Kriegler et al., 2013).

There has been recent controversy surrounding the net emissions of BECCS, specifically biofuels. Soil carbon, forest carbon loss, and the impact of large-scale sinks are a potential area of issue with net negative emissions (Wiltshire et al., 2015). The inputs into the production of energy crops must be carefully managed. The tractors used to apply fertilizers, pesticides, etc. increase the carbon emissions for BECCS. The additional nutrients to the soils for biomass also pose environmental concerns (Smith et al., 2016). The transportation emissions of energy crops from field to processing plants must be taken into consideration. Locating energy crops as close to where the energy crop will be converted into energy and the captured CO_2 will be stored will help reduce carbon emissions. Locating facilities close to both the available biomass and the storage facility can be challenging considering the amount of biomass that is needed.

Further Research

Future research for BECCS will need to address the many issues that surround the large-scale appropriation of ecologically productive land presumed by the technology. As noted above, there are different academic studies which show opposing views on the impact of bioenergy crops on the price of food and net GHG emissions. Further research is needed to understand the relationship between energy crop production and indirect land use change as the relationship is complex (Ahlgren & Di Lucia, 2014). Increasing crop efficiency should also be considered (Foley et al., 2011). Increasing crop yield would reduce the competition over land use with BECCS. A carbon price would rapidly increase the implementation of BECCS (Kriegler et al., 2013).

Conclusion

An advantage of BECCS is that it relies on technologies already in practice from energy crop production, biofuel manufacturing, and it would use carbon capture and storage technologies that have already seen extensive R&D for capturing CO_2 from fossil fuel use. The literature suggests that BECCS can remove a tonne of CO_2e at a price of $21 to $436. The wide range of estimates reflects the different energy assumptions about products, yield rates, cost calculation, activities, and capture rate among other assumptions/variables. At this range of prices, the literature shows that BECCS has the potential to remove between 0.04 and 32.1 $GtCO_2$e/year. Before the benefits of BECCS can be realized, some major challenges need to be overcome. To produce the necessary level of biomass, large swaths of land are required and this land requirement will clash with agriculture, urban, and forest growth. This competition may increase food prices and induce land use changes in other settings. Indirect land use change may completely offset any CO_2 savings. It will be necessary to develop a better understanding of biomass utilization trade-offs involving food and indirect land use change, increasing yields on agricultural lands, and the feasibility of cellulosic biofuels before BECCS plays the role foreseen in the IAM scenarios that include it.

Chapter 9:

Aquatic Bioenergy with Carbon Capture and Storage (Aquatic BECCS)

Aquatic Bioenergy with Carbon Capture and Storage (Aquatic BECCS)

Introduction

Aquatic Bioenergy with Carbon Capture and Storage (BECCS) is a speculative Carbon Dioxide Removal (CDR) option that absorbs carbon dioxide (CO_2) via plant growth in the ocean and then uses the harvested aquatic biomass to generate energy with capture and subsequent storage of CO_2 (N'yeurt et al., 2012). Although a variety of aquatic species might be suitable as a feedstock for Aquatic BECCS, much of the literature addresses aquatic macroalgae, which will be the primary focus of this analysis.

Key Findings

- *Aquatic BECCS is a speculative CDR option due to the lack of research regarding implementation impacts such as ecological and industry impact, economic costs, and CDR potential.*
- *Aquatic BECCS has the potential to capture and store 17.5 $GtCO_2e$/year at an approximate cost of \$18/tCO_2e.*
- *However, when all current literature is considered, the estimates range between 1.2 – 53 $GtCO_2e$/year at a cost between \$18 - \$138/tCO_2e.*

In this context, aquatic macroalgae refer to a variety of kelps and seaweeds, of which the five most produced genera include: Laminaria, Undaria, Porphyra, Eucheuma/Kappaphycus, and Gracilaria (Yarish & Pereira, 2008). Ideally, the expansion of such kelp and seaweed ecosystems for Aquatic BECCS would be managed in ways that promote biodiversity, increase primary productivity, as well as sequester CO_2 from oceans (Nellemann et al., 2009; N'yeurt et al., 2012). Some of its proponents have termed the expansion of seaweed ecosystems, ocean macroalgal afforestation (OMA). Once seaweed has grown, it can be harvested and processed through a biodigester to generate bioenergy. The resulting CO_2 can be captured and stored to affect a net removal of carbon from the atmosphere (N'yeurt et al., 2012).

Oceans occupy over 70% of the earth's surface area and are a substantial natural carbon sink. CO_2 is taken from the atmosphere both through diffusion and dissolution in ocean water and through photosynthesis by ocean organisms (Raven & Falkowski, 1999). The magnitude of the net ocean sink is approximately 5.9 $GtCO_2$/yr (IPCC, 2013). Currently, macroalgae occupy approximately 2% of the ocean surface (Duarte et al., 2005). That area has the potential to be expanded and used for seaweed production and harvesting to implement Aquatic BECCS (N'yeurt et al., 2012).

Other Aquatic Species That Can Be Used for Carbon Dioxide Removal (CDR)

Although this chapter focuses on macroalgae for CDR, other aquatic species can be used. For example, microalgae paired with bioenergy carbon capture and storage (BECCS) has been proposed and researched due to its high productivity of biomass creation and carbon capture. The main difference between macroalgal and microalgal production is the location of implementation. Microalgal production typically occurs in humanmade indoor and outdoor ponds compared to the oceans that use macroalgal production (Sayre, 2010). Water and land competition with other CDR options must be considered before implementing either of these technologies.

The Aquatic BECCS Process

Aquatic BECCS is a speculative CDR approach due to the lack of complete implementation both in large scale or pilot demonstrations which include both macroalgal afforestation combined with carbon capture and storage as well as the lack of empirical research conducted on Aquatic BECCS.

The Aquatic BECCS Process

As envisioned by (N'yeurt et al., 2012), the overall process would consist of the following steps:

1. Aquaculture: seaweed would be grown in a managed manner over an extensive area of the ocean, ideally fed by nutrients recovered from the later processing stage.
2. Harvest: seaweed is harvested and transported to a processing facility, which could be ocean-based in a location near the aquaculture site to minimize transportation costs and impacts.
3. Processing: various energy conversion processes might be used, but an attractive option is ocean-based anaerobic biodigestion. The resulting products would include biogas (primarily methane, CH_4), recovered nutrients, CO_2 and other wastes.
4. Carbon capture: the CO_2 resulting from anaerobic digestion is separated from the other product streams for piping to a storage location.
5. Storage: the captured CO_2 is permanently sequestered by one of several options (as discussed in Chapter 11 and below).
6. Recycle Plant Nutrients: the wastes that were produced during the processing phase will be transported back to an aquaculture location for additional fertilization.

Research has been conducted on macroalgal growth and carbon fixation, as well as, BECCS, however, very little, if any empirical research has been conducted on combining the two topics. In proposed Aquatic BECCS systems, the uptake of CO_2 from the atmosphere and its subsequent storage occur through separate processes and in different geographic locations (N'yeurt et al., 2012). This geographic separation occurs because harvesting is carried out in the ocean, whereas bioenergy generation, carbon capture, and carbon storage can be carried out in the ocean, on land or both. The CO_2 can also be stored in various ways, typically in a different location from either of the prior processes.

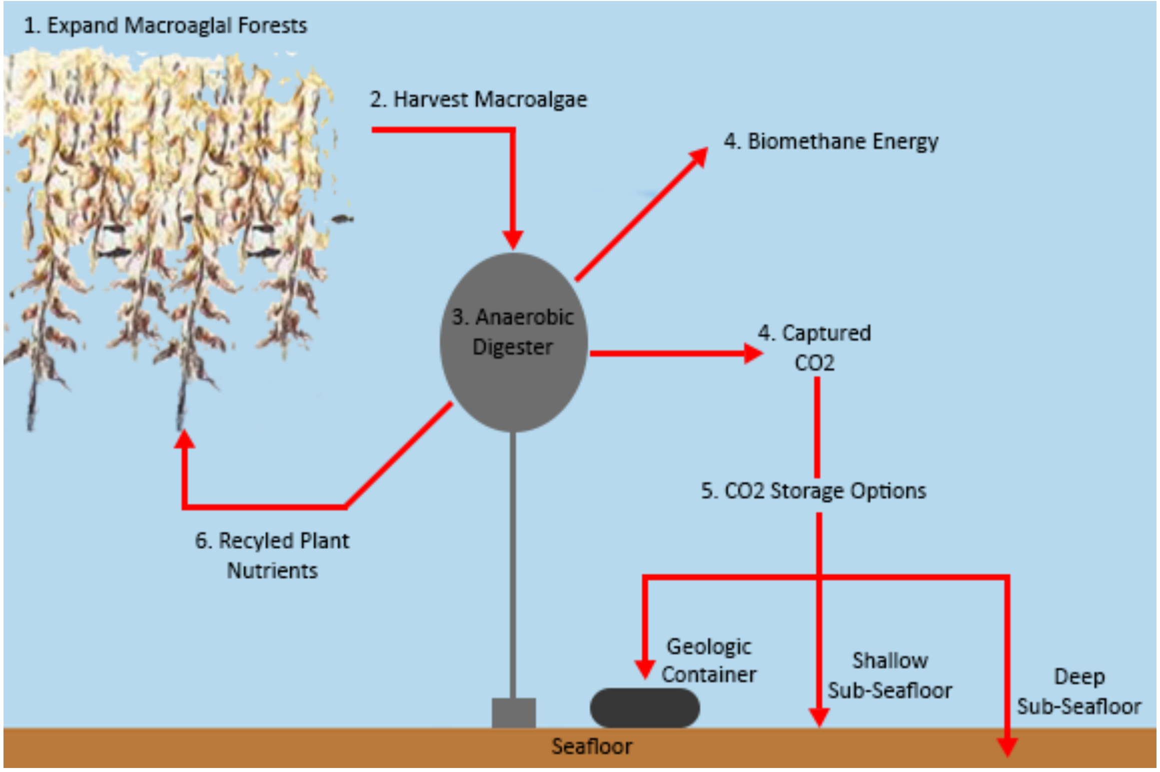

Figure 9-1: The Aquatic BECCS Process. Image adapted from N'yeurt et al., 2012.

A diagram of this approach, adapted from N'yeurt et al. (2012), is shown in Figure 9-1. Due to the lack of empirical research on Aquatic BECCS, sensitivity analyses have not been conducted on the effect of varying distances between seaweed production, biodigestion, and storage. However, it can be assumed that reducing the distance between seaweed production, biodigestion, and storage will impact both the net carbon emissions and costs of this CDR option.

Through the process of photosynthesis, seaweed takes in CO_2 from ocean water, converts it to organic material in the form of above-seafloor and below-seafloor biomass (e.g., blades, float, stripe, and holdfast) and then releases oxygen back into the ocean through respiration (Chung et al., 2012). Figure 9-2 depicts the major components of seaweed in which the organic material is stored. The rate of biomass growth is highly dependent on ambient CO_2 concentrations and nutrients, light, temperature, water motion, upwelling, salinity, and geographic location (Chynoweth, 2002; Ritschards, 1992).

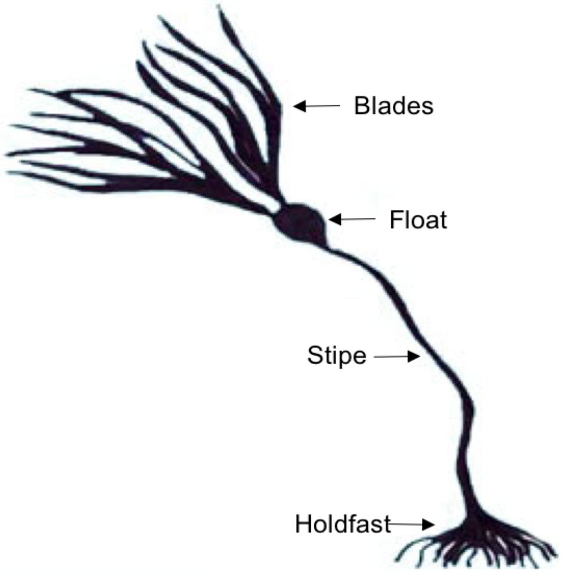

Figure 9-2: Structure of Marine Algae. Image adapted from Marine Education Society of Australasia, 2017.

Seaweed can then be harvested from the ocean floor using a variety of techniques (Roesijadi et al., 2010). These techniques are highly dependent on the type of macroalgae produced and the climate in which it was cultivated (Pereira & Yarish, 2008). The harvested macroalgae is then transported to anaerobic digestion containers, which could be located on site or kilometers away, where the macroalgae is decomposed creating three outputs: biogas, recyclable plant nutrients, and water (N'yeurt et al., 2012). The first output, biogas, is composed of 60% CH_4 and 40% CO_2 (Chynoweth, 2002; Hughes et al., 2012; N'yeurt et al., 2012). In principle, methane can be used as a gas or converted to liquid fuels such as jet fuel, diesel, methanol, and gasoline. The waste CO_2 from the digester can be captured, compressed and stored via various carbon capture and storage (CCS) technologies (N'yeurt et al., 2012). The second output, recyclable plant nutrients, can be transported from anaerobic digestion containers back to the macroalgal ecosystem where the nutrients would be carefully released to fertilize additional seaweed beds (N'yeurt et al., 2012).

Although biomass can be thermally gasified or directly dried and burned for energy generation (Bauen et al., 2009), the majority of studies on Aquatic BECCS have used anaerobic digestion. With the exception of the Hughes et al., (2012) study, which specifically stated that it uses anaerobic digestion in its modeling because this data was available, most studies did not specify why anaerobic digestion was used instead of other energy conversion technologies. Although not mentioned specifically in the literature, potential reasons could include various logistical reasons, as well as, the reduction of energy inputs from additional transportation and processing of the biomass.

For Aquatic BECCS to become a carbon negative process, the captured CO_2 must be safely and reliably stored. The storage methods for Aquatic BECCS mentioned in the literature include deep geologic storage, either under the earth's surface or seafloor; shallow sub-seafloor; solid snow; or in an artificial seafloor (N'yeurt et al., 2012). Although these are the methods mentioned in the Aquatic BECCS research, other methods could also be used such as storage within depleted oil and gas reservoirs, coal beds, saline aquifers, as well as, other geologic, terrestrial, and oceanic storage locations (Hepple & Benson, 2005). See Chapter 11 for the discussion of these storage options.

Carbon Dioxide Removal Potential of Aquatic Bioenergy with Carbon Capture and Storage (BECCS)

The projected CDR potential of Aquatic BECCS is highly dependent on assumptions about the area of seafloor usage and expansion, the geographic location of macroalgal forests/ecosystems, type of macroalgae cultivated, nutrients, light, temperature, water motion, upwelling, and salinity, as

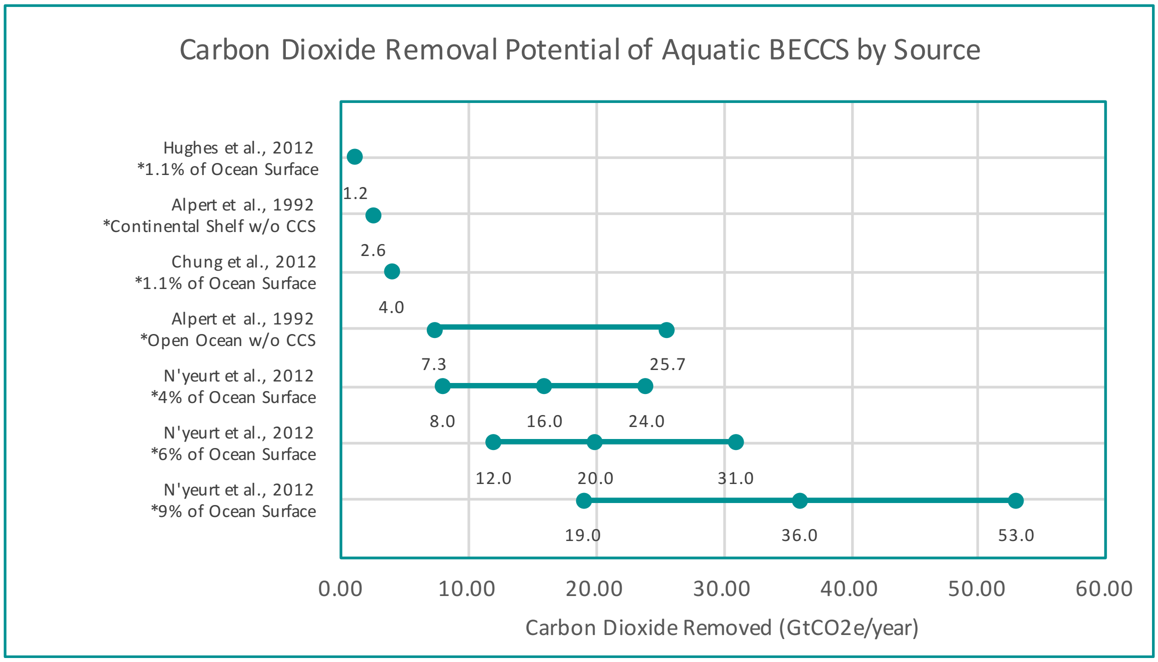

Figure 9-3: Graph of Carbon Dioxide Removal Potential in Gt of carbon dioxide equivalency per year of Aquatic BECCS. *Key assumptions made by the original author(s) or this research team are listed below the source.

well as, other variables (Chung et al., 2010; Chynoweth, 2002; Ritschards, 1992). Based on research, which varies primarily with area, geographic location, and species type, it is estimated that Aquatic BECCS has the potential to sequester and store between 1.2 - 53 $GtCO_2e$/year. The CDR potential of Aquatic BECCS is listed by source in Figure 9-3.

The wide variation in CDR potential, 1.2 - 53 $GtCO_2e$/year, is due to the wide range of major assumptions used in the different studies. A key parameter is the ocean area over which Aquatic BECCS would be implemented. Some of the studies specified an assumed area, others presented estimates based on a percent of ocean surface, and others stated quantities based on a per hectare basis. When a value was presented on a per hectare basis, we extrapolated it over an area that was deemed reasonable by Hughes et al. Given that macroalgae, both natural and planted, currently occupy approximately 2% of the ocean surface (Duarte et al., 2005), a reasonable area probably would be less than 2% of the ocean surface. Hughes et al. (2012) assume an area representing 1.1% of the ocean surface in their assessment, and we adopted this value as a reasonable estimate for extrapolating other estimates from the literature.

Chung et al.'s (2012) estimate, which was at the lower end of the range, was originally given as a per hectare figure. Recalculating their estimate assuming an area of 1.1% of the ocean surface, equated to a CDR potential of 4.0 $GtCO_2e$/year. When looking at the high end of the range,

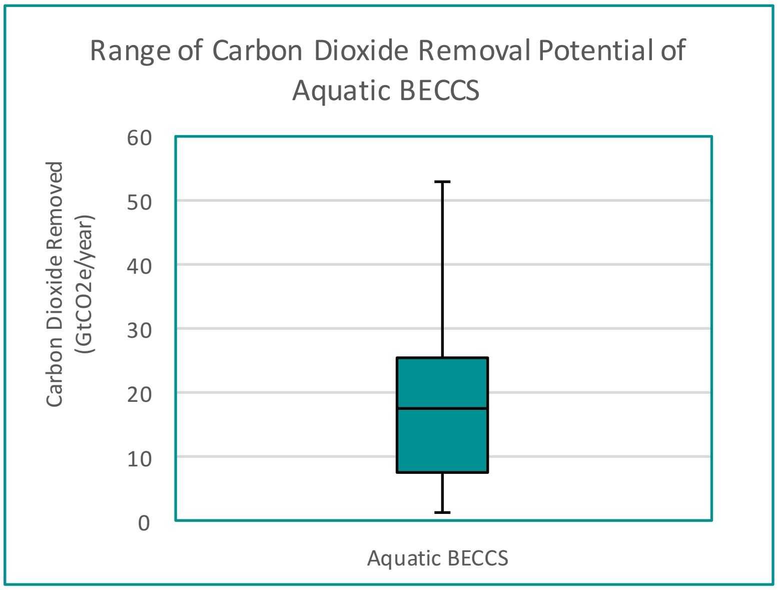

Figure 9-4: Graph of range of carbon dioxide removal potential in Gt of carbon dioxide equivalency per year of Aquatic BECCS. Min: 1.2; 1st: 7.5; Median: 17.5; 3rd: 25.3; Max: 53 $GtCO_2e$/year.

N'yeurt et al. (2012) assumed an area much larger than the 1.1% of the ocean surface. N'yuert et al. estimated a maximum CDR potential of 53 $GtCO_2e$/year based on an implementation area of 9% of the ocean surface.

As can be seen in Figure 9-3, there is substantial variation between the estimates/range of estimates from the studies, 1.2 - 53 $GtCO_2e$/year, therefore, further analysis was conducted. Using a quartile analysis, 50% of the data sources suggest that Aquatic BECCS could sequester and store between 7.5 - 25.3 $GtCO_2e$/year with a median figure of 17.5 $GtCO_2e$/year. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 9-4.

Economic Analysis of Aquatic Bioenergy with Carbon Capture and Storage (BECCS)

Aquatic BECCS is a speculative CDR approach that has been proposed but not often studied or implemented completely. Because of limited research on the economics, determining the financial cost of Aquatic BECCS is difficult. Although Aquatic BECCS utilizes natural processes (macroalgae growth), the process requires significant economic investments in resources and inputs. Depending on geographic location, type of anaerobic digestion technologies used, and type of CCS technologies used, Aquatic-BECCS costs between \$18 - \$138/tCO_2e. Estimated financial costs of Aquatic BECCS are listed by source in Figure 9-5.

Of the three estimates provided, only one of the sources, N'yeurt et al. (2012), estimates the cost of all the processes necessary for Aquatic BECCS, from CO_2 within the atmosphere to permanent

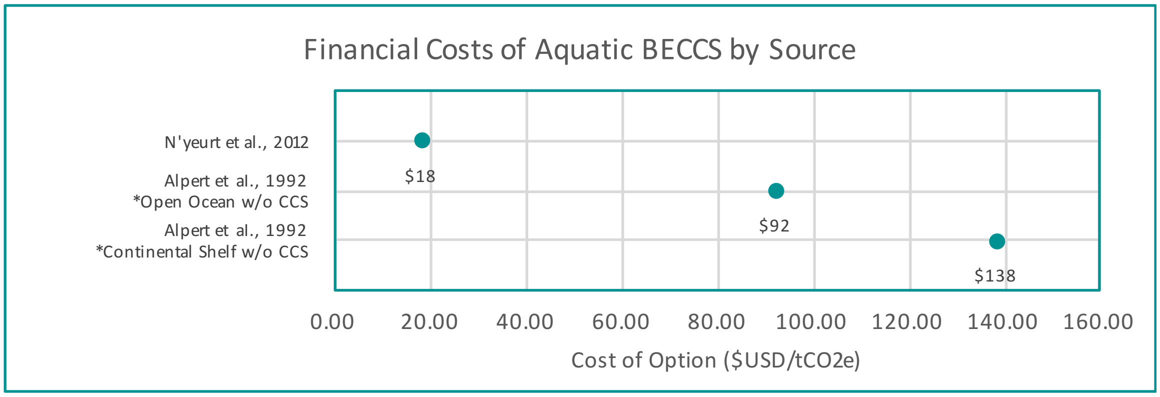

Figure 9-5: Graph of financial costs of Aquatic BECCS in 2015 US Dollars per tonne of carbon dioxide equivalency. *Key assumptions made by the original author(s) or this research team are listed below the source.

storage. The two other estimates, both much higher than the \$18/tCO_2e projected by N'yeurt et al., are from a 1990's analysis which focused solely on producing bioenergy from ocean macroalgal afforestation (OMA), excluding carbon capture and storage. The \$92/tCO_2e estimate is based on implementation in the open ocean and the \$138/tCO_2e estimate is based on implementation on the continental shelf. Both estimates exclude the costs of capturing, transporting, and storing CO_2 (Alpert et al., 1992 as cited in Ritschard, 1992).

Again, as can be seen in Figure 9-5, there is substantial variation among the estimates, \$18 - \$138/tCO_2e. Due to this wide variation as well as Alpert et al.'s exclusion of the carbon capture and storage processes, this research team has concluded that N'yeurt et al.'s estimate of \$18/tCO_2e is the most recent and realistic estimate of costs and this estimate will be used when comparing economic costs of Aquatic BECCS to the other options.

Geographic Restrictions

The geographic location where Aquatic BECCS can be implemented is fairly limited compared to other CDR approaches. Although Aquatic BECCS occurs in the ocean, which occupies over 70% of surface area on earth, the actual location where macroalgae can grow for harvesting is quite limited. Currently, macroalgae occupy approximately 2% of the ocean surface (Duarte et al., 2005). However, this estimate includes areas where macroalgae is growing naturally as well as planted for harvesting. When looking at the geographic scales examined in the literature, the largest and most optimistic estimate assumed use of 9% of the ocean surface (N'yeurt et al., 2012). That would amount to 32.5 million km^2, as area equal to 21.8% of the earth's land area (Central Intelligence Agency, 2016). In comparison, projections of large-scale terrestrial afforestation and reforestation, utilize 2.3% of the earth's land area (Central Intelligence Agency, 2016; Nilsson & Schopfhauser, 1995).

The natural growth of macroalgae is typically limited to coastal areas that have moderately shallow water. However, open ocean macroalgae afforestation is possible (Buck et al., 2004; Chung et al., 2012). As seen in Figure 9-6, the majority of seagrasses currently grown are near coastal regions. When looking solely at the seaweed aquaculture market, most seaweed grown for consumption occurs off the shores of China (54% of global production), Indonesia (27% of global production), Japan, the Philippines, and the Republic of Korea (Cottier-Cook, 2016). Because the type of macroalgae, as well as, water conditions typically dictate the best location for macroalgae growth and harvesting (Chung et al., 2010; Chynoweth, 2002; Ritschards, 1992), deciding where to implement Aquatic BECCS requires careful consideration. For example, if Aquatic BECCS were implemented with the Eucheuma, a group of red seaweed and one of the five most produced genera, an ideal location includes the following characteristics: a location past the lowest tide mark that allows for a water depth of 0.5 meters that receives plenty of sunlight, sandy bottom that has minimum amount of natural seaweed growth, medium water movement, a water temperatures between 25 °C to 30 °C, and a minimum water salinity of 28 parts per thousand (ppt) (Foscarini & Prakash, 1990). Although Eucheuma is similar to other seaweed species, the ideal location of implementation will be dependent upon the species or vice versa.

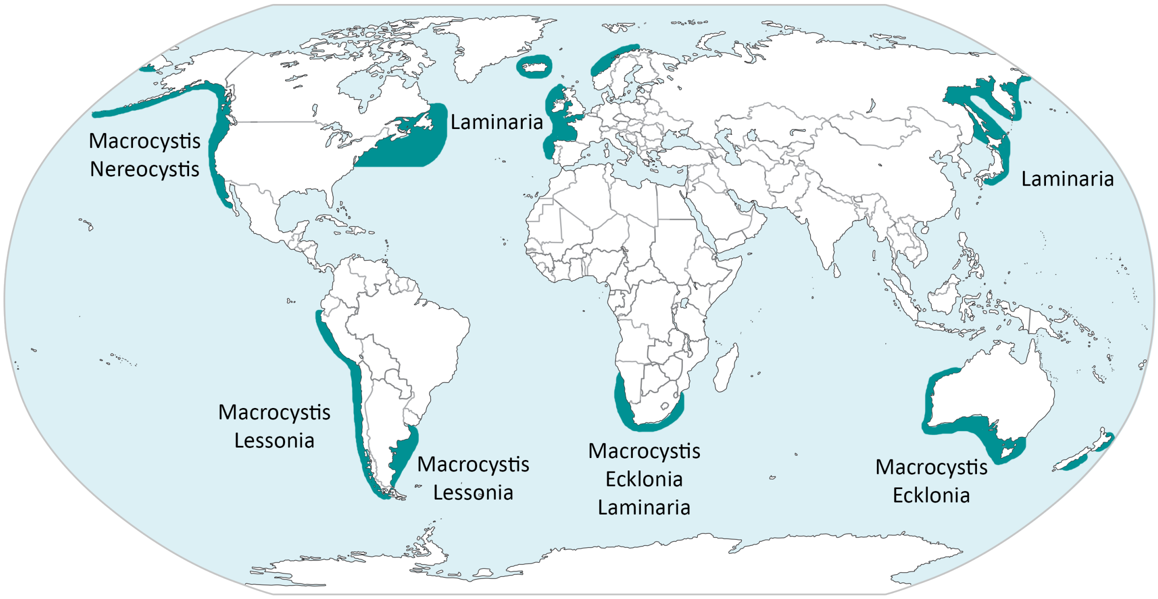

Figure 9-6: World geographic location of kelp forests. Image adapted from Steneck et al., 2002.

Policy Implications

Coastlines are typically seen as an area of economic development for many industries both in developed and developing countries. Because of the economic potential of coastlines, and for many other reasons, the UN Convention on the Law of the Sea was founded in 1982 to specifically define zones of water including the exclusive economic zone (EEZ). The exclusive economic zone dictates the control over the economic resources within waters up to 200 nautical miles away from the baseline, low-water line of the coast (United Nations, 1982). However, conflict can occur when baselines/coastlines are within 400 nautical miles of each other. Similar to other aquatic resources, conflicts over water rights are bound to occur when implementing Aquatic BECCS. It will be paramount for governments and their agencies to work together to ensure the implementation of Aquatic BECCS. Without this, Aquatic BECCS may require new, more specific policy.

In addition to interstate/country conflicts, intrastate/country conflicts could occur between the industries/constituents that utilize the coastline, such as recreation, tourism, fishing, energy, extraction, etc. In 2014, over 25 million metric tons of seaweed was harvested with a market value of seaweed aquaculture of approximately $6.4 million USD (Cottier-Cook, 2016). In comparison, global commercial fishing had a market value of approximately $230.4 billion in 2014 (Statistics MRS, 2015). Governmental agencies will have to use marine spatial planning (MSP) to work with their local communities and businesses to ensure collaboration is occurring between industries/constituents (Cottier-Cook, 2016). For example, governmental agencies will have to ensure collaboration between Aquatic BECCS, seaweed aquaculture for consumption, and the fishing market. Overall, due to the already-established UN Convention on the Law of the Seas, international policy will only have to be executed if mass implementation of Aquatic BECCS occurs. However, on a more local scale, policy might play a bigger role in reducing conflict between industries/constituents.

Benefits, Challenges, and Tradeoffs

There are many benefits of Aquatic BECCS besides sequestering and storing CO_2, as well as, the generation of bioenergy. For example, some of the benefits include: the creation of jobs within developing economies; the promotion of aquaculture and the associated benefits such as the creation of nursery grounds for fish and crustaceans, the reduction of dissolved nutrients which reduces occurrences of eutrophication, seabed protection which is harmed due to abrasive fishing techniques, as well as, the reduction of overfishing by providing alternative jobs in coastal economies (Cottier-Cook, 2016). Similar to all of the other CDR options, the benefits of Aquatic BECCS do not come without challenges and tradeoffs. Those challenges and tradeoffs include: life cycle emissions of Aquatic BECCS, disruption of aquatic ecosystems, and potential impermanence of storage depending on storage type.

Given the speculative nature of Aquatic BECCS, a great deal of uncertainty surrounds its overall net GHG emissions impact. Emissions can result from the associated industrial processes including biodigestion and bioenergy production, as well as, from the operations associated with growing the macroalgae, harvesting, and transporting the resulting biomass. Additional emissions can occur when producing and placing the biodigestion facilities and when transporting fuel, biogas,

CO_2, and nutrients to their usage or storage locations. Reducing distances between macroalgae production, biodigestion, and storage can help maximize the net CDR effectiveness of this option.

Another concern pertains to changes in the aquatic ecosystem that would occur when Aquatic BECCS were implemented in areas where extensive existing macroalgae did and did not naturally occur. Various ecosystem shifts could occur such as changing the structure and function of ecosystems and the associated food webs, cross-breeding among the wild and introduced species, as well as, the unplanned spread of the species beyond the intended area thus potentially damaging the surrounding ecosystem and its existing flora and fauna (Cottier-Cook, 2016). Implementation over vast areas, such as the 9% of ocean surface envisioned at the high end by N'yeurt et al. (2012), would entail a massive ocean ecosystem shift.

Finally, any option including a CCS component that relies on geological formations, permanence could potentially be a risk, especially with increasing seismic activity (Ellsworth, 2013). The main concern with CCS permanence is a risk of leakage that can occur causing a release of CO_2 back into the atmosphere. However, with the assumption of proper injection and management of the site, this CO_2 should be adequately stored for centuries. This assumption is based on a very low to zero percent leakage rate. A leakage rate of 0.01% to 0.001% a year would result in 90 to 99% of CO_2 remaining in the storage site after 1,000 years. A leakage rate of 1% a year would result in all CO_2 returning to the atmosphere after 400 years (Hepple & Benson, 2005).

Further Research

Further research on Aquatic BECCS is necessary to determine if it is a viable CDR option. Compared to the other seven CDR approaches examined in this report, very little theoretical and empirical research has been conducted regarding the viability, economic costs, and CDR potential of Aquatic BECCS. Additional research on the cost of Aquatic BECCS and the sequestration and storage potentials is imperative before governments consider promoting an Aquatic BECCS initiative. Additionally, a life cycle assessment (LCA) and a life cycle cost analysis (LCCA) should be conducted to analyze the full impacts of Aquatic BECCS including various storage options to account for the industrial process such as biodigestion, bioenergy production, and storage. Furthermore, the relationship between macroalgal production and other industries as well as potential interstate and intrastate policy issues associated with Aquatic BECCS must be addressed prior to implementation.

Conclusion

In conclusion, Aquatic BECCS is a speculative CDR option due to the lack of research regarding implementation impacts such as ecological and industry impact, economic costs, and CDR potential. It is estimated that Aquatic BECCS could capture and store about 17.5 $GtCO_2e$/year at an approximate cost of \$18/tCO_2e. However, when all current literature is considered, estimates for CDR potential range between 1.2 – 53 $GtCO_2e$/year at a price between \$18 - \$138/tCO_2e. Further research regarding implementation impacts such as ecological and industry impact, economic costs, and CDR potential of Aquatic BECCS is necessary before mass implementation.

Chapter 10:

Ocean Fertilization

Ocean Fertilization

Introduction

Key Findings

- *Ocean fertilization is a speculative CDR option due to the lack of large scale implementation as well as the ecosystem impact concerns of large scale ocean fertilization.*
- *Ocean Fertilization has the potential to capture and store 3.7 $GtCO_2e$/year at an approximate cost of \$32/tCO_2e.*
- *However, when all current literature is considered, the estimates range between 1.0 – 11.2 $GtCO_2e$/year at a cost between \$9 - \$288/tCO_2e.*

Ocean fertilization, sometimes known as ocean nourishment (Jones, 2014), is a proposed Carbon Dioxide Removal (CDR) option that purposefully introduces specific nutrients into the ocean to stimulate growth in marine microscopic organisms (phytoplankton), thus removing carbon dioxide (CO_2) from the atmosphere via photosynthesis by ocean organisms (NRC, 2015; Williamson et al., 2012). Three nutrients that are typically thought of as the limiting nutrients for phytoplankton growth are iron, nitrogen, and phosphorous (Williamson et al., 2012). Most of the earth's oceans are limited by nitrogen and phosphorous causing phytoplankton growth to be limited in those areas. However, in approximately one-third of the earth's oceans, iron is the limiting nutrient; in these areas, the amount of nitrogen and phosphorus is high enough to promote phytoplankton growth. However, additional iron is needed for that growth to occur (Williamson et al., 2012).

Oceans, as a natural sink, allow for CO_2 to be taken from the atmosphere and stored in the ocean both through diffusion and dissolution in ocean water and through photosynthesis by ocean organisms (Raven & Falkowski, 1999). The magnitude of the net ocean sink is approximately 5.9 $GtCO_2$/yr (IPCC, 2013). Considering oceans occupy over 70% of the earth's surface area (Raven & Falkowski, 1999), a CDR approach that utilizes such a large percentage of the earth's surface sounds promising. However, the introduction of these nutrients inevitably changes the surrounding ecosystem, a major concern of this approach, limiting its geographic application (Bertram, 2008; Denman, 2008; NRC, 2015; Powell, 2008b).

Ocean fertilization has been implemented in zones of the ocean called desolate zones, also known as high nutrient, low chlorophyll (HNLC) zones which lack a critical nutrient, therefore prohibiting phytoplankton or other aquatic life from growing (NASA, 2017b; Williamson et al., 2012). This limiting factor stops the growth of phytoplankton, which is a major consumer of CO_2 stored in the ocean (NASA, 2017b). Intentionally adding this limiting nutrient to these areas will promote growth of phytoplankton leading to the sequestration and storage of additional CO_2 (Williamson et al., 2012).

Figure 10-1: Map of ocean fertilization experiments between 1993-2009. Image adapted from Williamson et al., 2012.

The Ocean Fertilization Process

Ocean fertilization is a speculative CDR option due to its lack of large-scale implementation and related research, which in turn is due to the concerns about potential ecosystem side effects. Currently, there have been several small-scale demonstration experiments conducted on ocean fertilization (Williamson et al., 2012). See Figure 10-1 for a map of ocean fertilization experiments between 1993-2009.

Ocean fertilization utilizes phytoplankton's natural ability to uptake and store CO_2. For this process to occur, the limiting nutrient must be added to the ocean water and is typically transported to the area by an ocean vessel. Adding the limiting nutrient, allows for the growth of phytoplankton, increasing primary productivity within these zones, which previously did not host vast amounts of aquatic life (Bertram, 2010). Through the process of photosynthesis, phytoplankton uptake CO_2 from ocean water and store carbon within their biomass by building particulate organic carbon (POC). The carbon remains within the biomass of the phytoplankton until it is consumed by aquatic life higher on the food chain, typically zooplankton, or remineralized by bacteria causing the carbon to return to its original state as dissolved or inorganic carbon within the ocean water (Bertram, 2010).

However, if not consumed or remineralized, some dead and living phytoplankton and the associated carbon, known as export production, sink or are forced by mixing and advection currents to deep ocean depths where they are buried with sediments on the ocean floor (Denman, 2008). Due to the potential of being consumed by aquatic life, remineralized, or even transformed back into dissolved nutrients and inorganic carbon on the ocean floor through the process of diagenesis, the fraction of phytoplankton and associated carbon that is buried is small (Denman, 2008). Only 1-15% of the carbon sinks below 500 meters, allowing for potential burial (Powell, 2008a). A diagram of this process is shown in Figure 10-2.

The Ocean Fertilization Process

As discussed by Bertram (2010), Denman (2008), and Powell (2008b) as well as others, the overall process would consist of the following steps:

1. Addition of the Limiting Nutrient: based on a region's limiting nutrient, iron, nitrogen, or phosphorous would be transported via an ocean vessel to this region and would be poured into the surrounding water.
2. Carbon Uptake: no longer limited due to the addition of the limiting nutrient, phytoplankton would grow, uptaking CO_2 from the surrounding water (See step 2 in Figure 10.2).
3. Carbon Storage: phytoplankton and the associated carbon subsequently die or sink to deep ocean depths where it is buried with ocean floor sediments (See steps 5-8 in Figure 10.2).

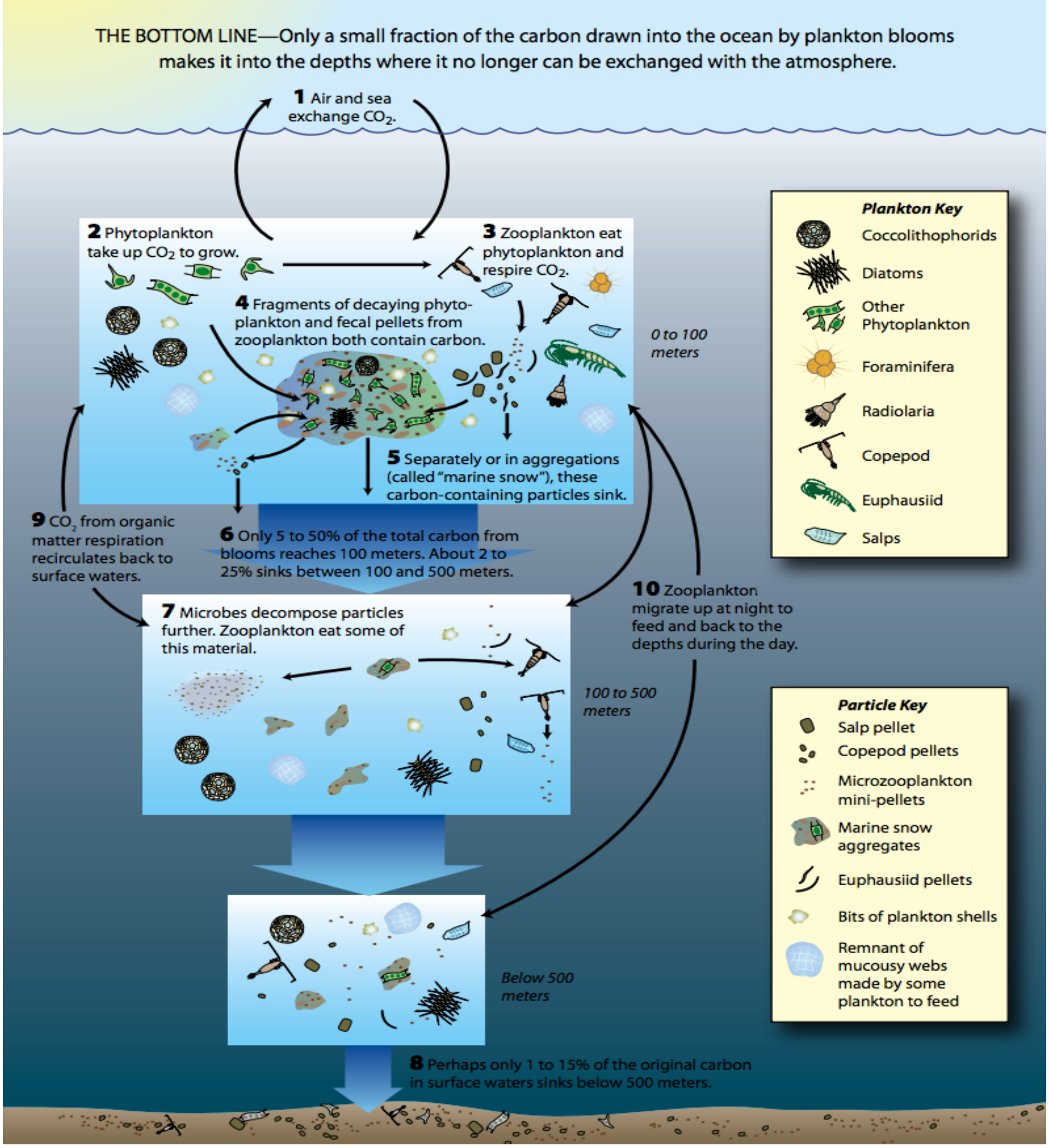

Figure 10-2: The Ocean Fertilization Process. Image from Powell, 2008a.

Carbon Dioxide Removal Potential of Ocean Fertilization

The projected CDR potential of ocean fertilization is dependent on the amount of the limiting factor added, status of phytoplankton pre-fertilization, grazing pressure by zooplankton, the amount of time the atmosphere had contact with the fertilized area, stratification, and mixing of the water via upwelling and advection, sinking and burial rates, and light conditions (Bertram, 2008; Denman, 2008; Mayo-Ramsay, 2010; Williamson et al., 2012). Based on research, which varies primarily on the area in the ocean where the study was conducted, it is estimated that ocean fertilization has the potential to sequester and store between 1 - 11.2 $GtCO_2e$/year. The CDR potential of ocean fertilization is listed by source in Figure 10-3.

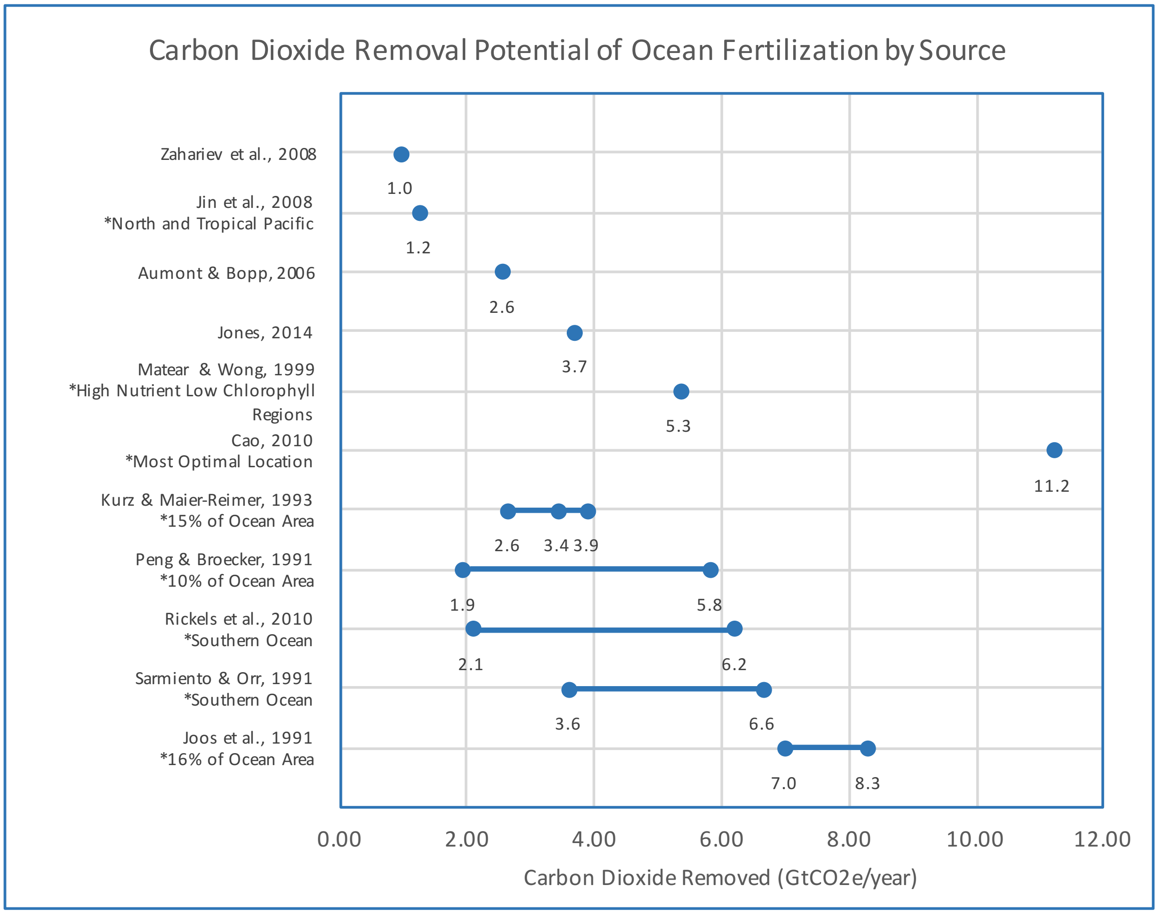

Figure 10-3: Graph of Carbon Dioxide Removal Potential in Gt of carbon dioxide equivalency per year of Ocean Fertilization. *Key assumptions made by the original author(s) or this research team are listed below the source.

Chapter 10: Ocean Fertilization

The variation in CDR potential, 1 - 11.2 $GtCO_2e$/year, is due to the wide range of major assumptions used in the different studies. A key parameter is the ocean area in which ocean fertilization is theoretically implemented. Some of the studies specified an assumed area, others presented estimates based on a percent of the ocean surface, and others specified quantities based on the most optimal oceanic locations. For example, Aumont & Bopp (2006), assumed the entire ocean as an implementation area for iron fertilization, whereas, other studies specified specific regions, such as the entire North and Tropical Pacific Ocean (Jin et al., 2008), the temperate ocean (Jones, 2014), the Southern Ocean (Joos et al., 1991; Kurz & Maier-Reimer, 1993; Rickels et al., 2010; Sarmiento & Orr, 1991), and any high-nutrient, low-chlorophyll (HNLC) regions (Matear & Wong, 1999). Alternatively, some studies based their assessment on a percent of the world's oceans, for example, Peng & Broecker, 1991, assumed implementation in the Antarctic Ocean, also known as the Southern Ocean, which they assumed to be equivalent to 10% of the world's oceans, whereas, Joos et al., 1991, assumed 16% of the world's oceans located in the Southern Ocean (Joos et al., 1991; Peng & Broecker, 1991).

A second key parameter that produced variation in the estimates is related to when, temporally, ocean fertilization is implemented. Although not all studies discussed this parameter, a few of the studies specifically stated their assumptions. For example, Matear & Wong (1993), Jones (2014), and Joos et al., (1991), specifically stated that ocean fertilization must be a continuous on-going process, meaning the limiting nutrient must be continuously added without major breaks in time (Jones, 2014; Joos et al., 1991; Matear & Wong, 1991). The reason behind continuous on-going fertilization is the need to avoid re-exposure of CO_2 back into the atmosphere, thus defeating the purpose of this CDR option (Jones, 2014). Additionally, Kurz & Maier-Reimer (1993) only measured fertilization effects during summer months (located in the Southern hemisphere) and did not measure the effects of fertilization between April through September because water conditions are not supportive of biological production during those months (Kurz & Maier-Reimer, 1993).

A third key parameter that produced variation in the estimates within and among studies is the use of different CO_2 emission scenarios. Although some of the studies used their own assumptions regarding CO_2 emission scenarios, a lot of the studies relied upon IPCC scenarios. For example, Kurz & Maier-Reimer (1993) used both their own scenarios as well as IPCC scenarios. Kurz & Maier-Reimer (1993) modeled three scenarios with the following attributes: (1) ocean iron fertilization without anthropogenic CO_2 emissions since pre-industrial period, (2) constant rate emission of 1990's 6.35 Gt C/y, (3) Ocean Iron Fertilization with IPCC business as usual scenario A (Kurz & Maier-Reimer, 1993). Alternatively, Cao (2010) and Rickels et al. (2010) relied on the IPCC A2 scenario in their study (Cao, 2010; Rickels et al., 2010). Lastly, the limiting nutrient used with ocean fertilization is typically a key parameter differentiating results. However, all of the studies present in Figure 10-3 are based on using iron as a limiting nutrient except Jones (2014), which used ammonia hydroxide (nitrogen) in their scenario (Jones, 2014).

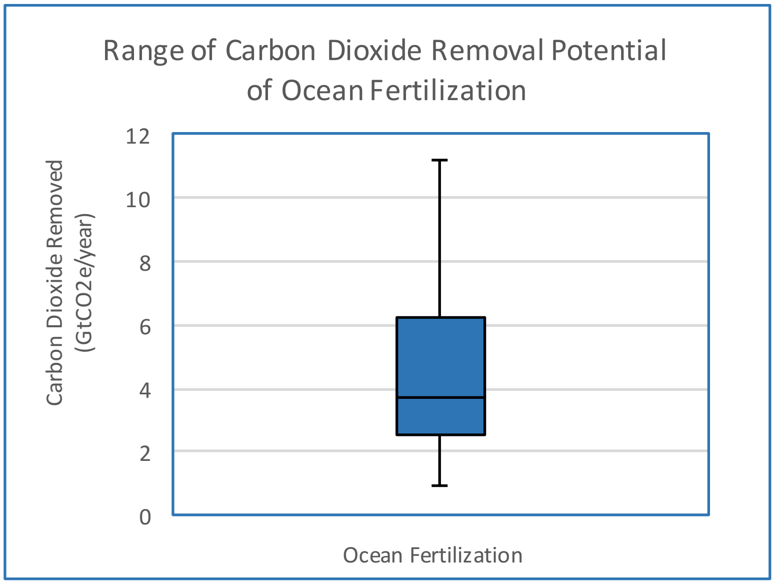

Figure 10-4: Graph of range of carbon dioxide removal potential in Gt of carbon dioxide equivalency per year of Ocean Fertilization. Min: 1.0; 1st: 2.6; Median: 3.7; 3rd: 6.2; Max: 11.2 $GtCO_2e$/year.

As can be seen in Figure 10-3, there is substantial variation between the estimates/range of estimates from the studies, 1 – 11.2 $GtCO_2e$/year, therefore, further analysis was conducted. Using a quartile analysis, 50% of the data sources suggest that ocean fertilization could sequester and store between 2.6 – 6.2 $GtCO_2e$/year with a median figure of 3.7 $GtCO_2e$/year. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 10-4.

Economic Analysis of Ocean Fertilization

Ocean fertilization is an aquatic management methodology that does not require significant capital expenditures or the development of new technologies. Depending on the limiting nutrient production cost, travel distance (delivery cost), and potential long-term sequestration and storage losses (Jones, 2014), the cost of ocean fertilization ranges from approximately \$9/tCO_2e to \$288/tCO_2e. Estimated financial costs of ocean fertilization are listed by source in Figure 10-5.

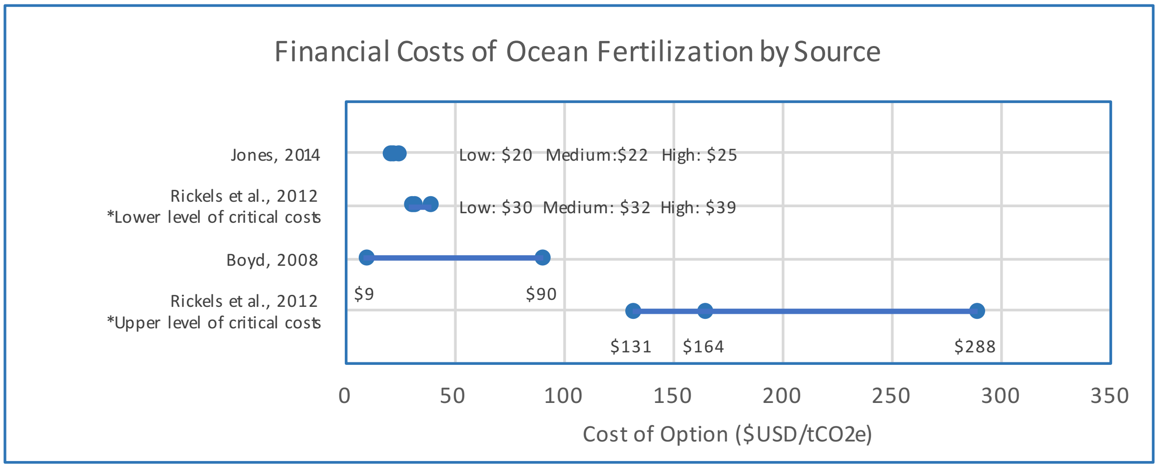

Figure 10-5: Graph of financial costs of Ocean Fertilization in 2015 US Dollars per tonne of carbon dioxide equivalency. *Key assumptions made by the original author(s) or this research team are listed below the source.

As seen in Figure 10-5, there are three recent sources that provide economic cost data. Primarily, these studies vary based on the categories of costs included, as well as, the approach that was used to derive a cost estimate. For example, Jones (2014) included transportation, ammonia, and overhead costs, whereas Boyd (2008) stated that only direct costs of fertilization were assumed. Thus, their cost estimates cannot be applied to large-scale ocean fertilization projects (Boyd, 2008; Jones, 2014). Alternatively, both Rickels et al. (2012) estimates are based on a market approach that used a, “topdown, calibrated abatement cost function” (Rickels et al., 2012). The distinction between Rickels et al.’s two estimates is the use of lower vs upper critical costs. As defined by Rickels et al. (2012), “the critical unit costs are defined as those that would make an emitter indifferent between various abatement options” (Rickels et al., 2012).

Again, as can be seen in Figure 10-5, there is substantial variation among the estimates, $9 - $288/tCO$_2$e, therefore, further analysis was conducted. Based on a quartile analysis from all sources, 50% of the estimates suggest ocean fertilization costs between $23 - $111/tCO$_2$e with a median cost of $32/tCO$_2$e. This quartile analysis is graphically depicted as a box-and-whisker plot in Figure 10-6.

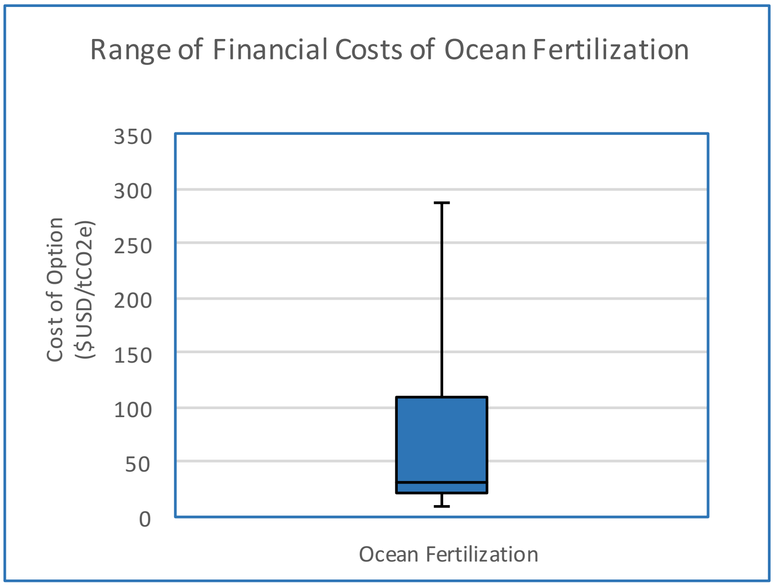

Figure 10-6: Graph of range of financial costs of Ocean Fertilization in 2015 US Dollars per tonne of carbon dioxide equivalency. Min: 9; 1st: 23; Median: 32; 3rd: 111; Max: 288 $USD/tCO_2e.

Geographic Restrictions

The geographic location where ocean fertilization theoretically can be implemented is quite large, considering oceans occupy over 70% of the earth's area (Raven & Falkowski, 1999). However, due to the potential negative implications for adding mass amounts of nutrients into aquatic ecosystems, ocean fertilization is primarily targeted towards areas of the ocean called desolate zones (NASA, 2017a). Desolate zones, also known as high-nutrient, low-chlorophyll (HNLC) zones, are areas known for having high nutrients, few phytoplankton or other aquatic life, and lacking an essential nutrient, typically referred to as a limiting factor (NASA, 2017b; Williamson et al., 2012). Known desolate zones are located in the North Pacific Ocean, the equatorial region on the Pacific Ocean, and the Antarctic (Southern) Ocean (NASA, 2017a). Figure 10-7 represents a map of global average chlorophyll concentrations in 1997. As can be seen, higher levels of chlorophyll, thus phytoplankton, are in the northern hemisphere and near coastlines.

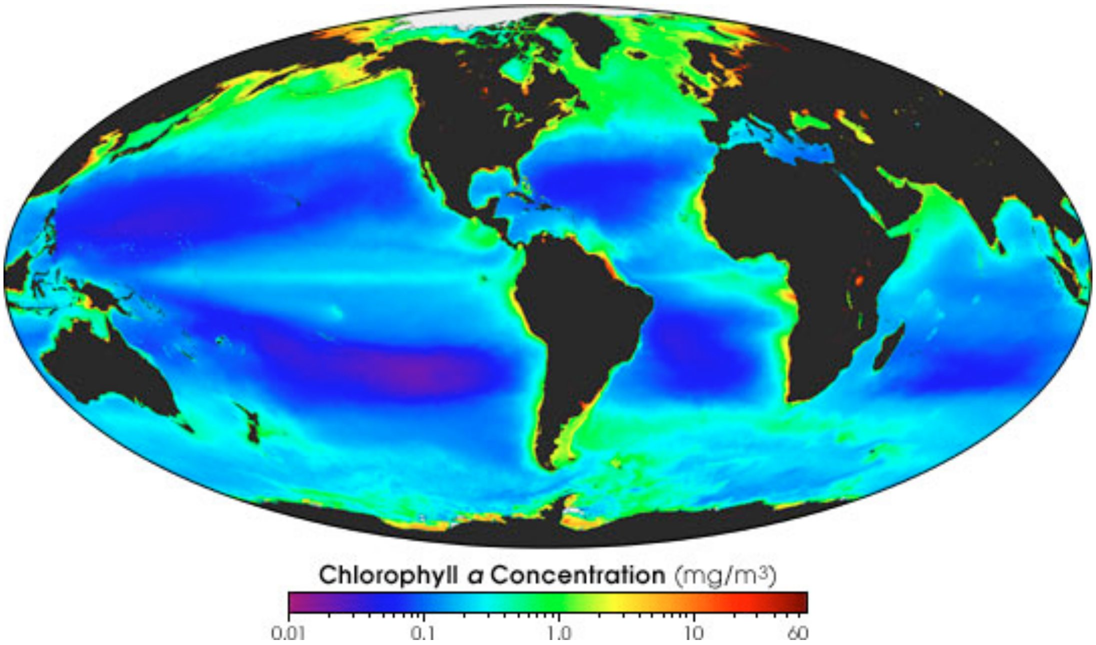

Figure 10-7: Map of Chlorophyll concentrations. Image from NASA, 2017c.

Policy Implications

The main question in regards to ocean fertilization is who should be responsible for implementation, as well as, who should be responsible for the economic costs of implementation. Considering this option will be implemented in HNLC zones, which typically are not located near coastlines and are across various geographic locations in oceans, developing policies with respect to allocating costs and responsibility for the option potentially could be troublesome. Typically, when determining water rights, the 1982 UN Convention on the Law of the Sea is used to settle any disputes. The UN Convention on the Law of the Sea defined zones of water including the exclusive economic zone (EEZ). The exclusive economic zone dictates the control over the economic resources in waters up to 200 nautical miles away from the baseline, the low-water line of the coast. Any distance past the EEZ is considered international waters which do not give any specific country sovereignty (United Nations, 1982). Implementation of ocean fertilization will most likely occur in international waters and could potentially cause disputes between countries. Creating and agreeing on water policies related to ocean fertilization will be critical before implementation occurs.

Benefits, Challenges, and Tradeoffs

One of the major benefits of ocean fertilization is the lack of competition this CDR approach will receive in comparison to the other approaches. First, by its very nature, ocean fertilization does not occur on land, thus it is not affected by land competition. However, oceans are typically regarded as global commons, thus conflicts over use may rise between nations. Second, ocean fertilization would be implemented in zones not near the coastline and with little aquatic life (NASA, 2017a). Thus competition over fishing, recreation, tourism, aquaculture, and other industries would be minimal. Similar to other CDR approaches, the implementation of ocean fertilization has major challenges and tradeoffs. These challenges have been seen in the past, for example, a proposed pilot project in the Galapagos Islands created so much concern and outrage by society that the government of Ecuador eventually decided to cancel the pilot project (Seed Map, 2017). These challenges and tradeoffs are directly related to ecosystem impacts of adding mass quantities of iron, nitrogen, or phosphorus to an area of the ocean.

Although ocean fertilization is only supposed to occur in desolate zones of the ocean, where very little aquatic life exists, little is known about large-scale, long-term impacts of adding tonnes of iron, nitrogen, or phosphorous to the ocean. While there have been no observed negative impacts of the small-scale experiments that have already occurred, many scientists have speculated that these studies do not represent the potential negative damage that could be caused by large-scale implementation due to the small size of these experiments (Powell, 2008b). One of the major effects that could occur is an ecosystem shift that affects multiple levels of the food chain (NRC, 2015). First, by adding the limiting nutrient, multiple organisms, including phytoplankton, will utilize it as a resource, increasing the population of these organisms. This increase will impact phytoplankton's own trophic level, as well as, the rest of the food chain (Powell, 2008b).

Another food chain impact that is of concern to scientists is the potential for harmful algal blooms. Research has suggested that the algal blooms caused by urea (nitrogen) fertilization could cause eutrophication leading to hypoxic and anoxic zones impacting the fish population and potentially releasing the CO_2 that was sequestered by the algae, as well as, methane, nitrogen, and nitrous oxide (Glibert et al., 2008). Additionally, it is predicted that toxic dinoflagellates are likely to thrive and dominate these areas, decreasing species diversity, as well as, increasing the population of algae that has toxic effects on fish and subsequently human health if consumed (Glibert et al., 2008).

Further Research

Further research on Ocean Fertilization is necessary to determine more precise sequestration efficiencies, as well as, the direct and indirect impacts of large-scale ocean fertilization. Compared to the other seven CDR options examined in this report, the amount of research conducted on ocean fertilization lies in the middle of the spectrum. Although ocean fertilization has not been implemented and studied on a large scale, like afforestation and reforestation, there have been a handful of patch scale studies conducted. However, very little is known about the potential direct and indirect impacts of ocean fertilization on the surrounding ecosystems (Powell, 2008b). Furthermore, due to the lack of accurate efficiency measurements and estimates (NRC, 2015), additional research on the impacts of large-scale ocean fertilization implementation, as well as, the sequestration and storage efficiency and potential is imperative before governments consider promoting an ocean fertilization initiative.

Conclusion

In conclusion, ocean fertilization is a speculative CDR option due to the lack of large-scale implementation, as well as, the ecosystem impact concerns of large-scale ocean fertilization. Ocean fertilization has a potential likelihood to capture and store 3.7 $GtCO_2e$/year at an approximate cost of \$32/tCO_2e. However, when all current literature is considered, estimates range between 1.0 – 11.2 $GtCO_2e$/year at a cost between \$9 - \$288/tCO_2e. Further research regarding ecosystem impacts of large-scale ocean fertilization is necessary before mass implementation.

Chapter 11:

Geologic Storage

Geologic Storage

Introduction

After carbon dioxide (CO_2) is captured and concentrated, it must be stored so it does not re-enter the atmosphere. Geologic storage is a way to inject concentrated CO_2 underground for permanent storage. Five geologic storage options are discussed in this chapter; saline aquifers, depleted oil and gas wells, depleted coal seams, basalt formations, and offshore sediments. The physical trapping of the CO_2 is the short-term goal with the long-term goal of using geochemical processes in order for the CO_2 to become a part of the sediment (Höller & Viebahn, 2016).

There are many uncertainties that make estimating capacity difficult (Höller & Viebahn, 2016). Benson has called geological storage the only mature option that does not have huge obstacles or concerns (Benson et al., 2012). The IPCC says there is sufficient capacity for 100 years of storage, with estimates ranging anywhere from 200 - 2,000 $GtCO_2$ storage potential (Benson et al., 2012). A lack of capacity is not a concern (Dooley, 2013). Total estimated capacity (for Saline, Oil/Gas, and Coal) from a meta-analysis by Dooley (2013) is determined based off characteristics, theoretical capacity is estimated at 35,300 $GtCO_2$; effective capacity at 13,500 $GtCO_2$; practical capacity at 3,900 $GtCO_2$; matched capacity at 290 $GtCO_2$; and utilized capacity 0.034 $GtCO_2$. This meta-analysis is based off 34 academic articles. Theoretical capacity includes all the geologic storage including sites that are unrealistic for injection. It is the maximum upper limit. The effective capacity reduces the theoretical amount by engineering and geological constraints. Practical capacity reduces effective by "considering technical, legal and regulatory, infrastructure, and general economic barriers to CO_2 geological storage." Finally, matched capacity reduces practical by matching "large stationary CO_2 sources with geological storage sites that are adequate in terms of capacity, injectivity and supply rate" (Bachu et al., 2007). For effective storage, researchers must identify sites that have adequate porosity, permeability, and impermeable cap rocks (Schrag, 2009). With the assumption of proper injection and management of a site, the CO_2 should be adequately stored for centuries. This assumption implies a very low to zero percent leakage rate. A leakage rate of 0.01% to 0.001% a year would result in 90 to 99% of the CO_2 remaining in the storage site after 1,000 years. A leakage rate of 1% a year would result in all CO_2 returning to the atmosphere after 400 years (Hepple et al., 2005).

Saline Aquifers

A saline aquifer is a body of deep permeable sedimentary rock that is saturated with dissolved salt (IPCC, 2005). Saline aquifers are typically located at depths below 800 meters below sea level (Bentham & Kirby, 2005) and contain water that cannot be used for human consumption or agriculture (IPCC, 2005). For CO_2 to be stored in a saline aquifer, concentrated CO_2 must be pumped into the pores of the rocks replacing the solution of dissolved salt and water (Benson et al., 2012). Through a chemical reaction after hundreds or thousands of years, some of the CO_2 is transformed into carbonate minerals. These carbonate minerals become part of the rock formation (Gunter et al. 2004).

In order for a saline aquifer to be considered for CO_2 storage, there are several properties that must be met including location, porosity and permeability, and depth. For example, the saline aquifer must be located under a “cap rock” which restricts the leakage and release of CO_2. Additionally, it must be located in a geologically stable location in order to avoid leakage from tectonic activity. This leakage is a major concern for geologic storage options. The saline aquifer must be porous and permeable enough in order to allow for the injection and storage of CO_2. Lastly, as stated earlier, the saline aquifer should be located 800 meters below sea level. Saline aquifers are estimated to have the largest CO_2 storage capacity compared to the other geologic storage options. Saline aquifers have an estimated potential to storage between 4,000 - 23,000 $GtCO_2$ (Benson et al., 2012). This storage capacity is highly dependent upon the volume of the reservoir, net and gross usable space of a rock, average porosity of the saline formation, density of CO_2, as well as a storage efficiency (Höller & Viebahn, 2016).

Depleted Oil and Gas Wells

Upon depletion of recoverable oil and gas, the oil or gas field can transition to a new purpose: a storage facility. Injecting CO_2 into depleted oil and gas wells as a means for permanent storage can take advantage of previous investment from oil and gas companies. The well will already have been established, injection equipment will already be on-site, and geologic mapping to understand the characteristics of the geologic formation will have been previously performed. Even before the useful life of a well is complete, CO_2 storage can occur. CO_2 injection in oil fields has been happening for decades as enhanced oil recovery (EOR). Benson (2012) estimated the total storage potential for depleted oil and gas fields to be between 675 and 900 $GtCO_2$. As the main objective of injecting CO_2 into oil and gas fields is fuel recovery (Höller & Viebahn, 2016), additional information regarding injecting CO_2 into depleted oil and gas fields can be found in the discussion of EOR in Chapter 13.

Depleted Coal Seams

Depleted coal seams refer to the coal that cannot be mined for a given reason. For instance, the coal may be buried too deep to make it profitable to recover under current mining technologies. However, the un-mineable coal seams are an attractive option to sequester CO_2 since the surface of coal provides a porous media to absorb CO_2 (Bae et al., 2006). More importantly, coal absorbs CO_2 more readily than methane (CH_4), which is also found in coal (Dahowski et al., 2004). This allows for the possibility of storing CO_2 while at the same time recovering coalbed methane (Dahowski et al., 2004). Known as enhanced coalbed methane recovery (CO_2-ECBM), this process is similar to enhanced oil recovery.

Considering nearly 50% of coal production occurs in China, ECBM can be a promising method to reduce CO_2 emission in China. As evaluated by Fang (2014), the low, medium, and high estimates of CO_2 storage potential in China are 15.6 $GtCO_2$, 101 $GtCO_2$ and 389 $GtCO_2$, respectively. Holler (2016) also adopted a basin-specific analysis in order to assess the effective potential storage capacity of coal seams in China which equated to around 65 Gt of CO_2. However, Benson (2012) estimated the total storage potential of 93 - 150 $GtCO_2$ globally. From the existing estimates, the great variances show that there is uncertainty in regards to the CO_2 storage capacity including limited geological knowledge, lack of large-scale research on CO_2 injection, and different parameters in different assessing methods (Holler et al., 2016).

Basalt Storage

Basalt storage is a geologic storage option that geochemically traps CO_2 through mineralization in basalt or peridotite rock formations. Similar to *ex situ* accelerated weathering (discussed in Chapter 6), basalt storage uses the *in situ* reaction of CO_2 with calcium, magnesium, and iron silicate minerals to form a stable carbonate mineral (Matter et al., 2016). A pure stream of CO_2 or a water solution containing CO_2 is injected into basalt or peridotite rock, which is composed of over 25% of the required reactant minerals, by mass (Gislason & Oelkers, 2014). The resulting calcite, dolomite, magnesite, or siderite minerals are stable (Gislason, et al., 2010), which effectively removes the potential for gas leakage (Matter, et al., 2016). In this way, basalt storage distinguishes itself from other storage options that risk the escape of CO_2 gas or brine water (Matter & Keleman, 2009; Matter et al., 2016).

Basalt storage is currently a speculative storage option that has not been pursued at mass scale. A pilot project called CarbFix in Iceland established that over 95% of CO_2 injected as a dissolved solution was mineralized within two years (Matter et al., 2016). A second pilot project, the Big Sky Carbon Sequestration Partnership (BSCSP) near Wallula, Washington in the United States, is evaluating the reactivity of pure CO_2 without the presence of water to accelerate the reaction (Gislason & Oelkers, 2014). Laboratory and pilot project results indicate that the amount of water needed to accelerate the carbon mineralization process decreases with temperature, lower salinity, and increased pressure (Gislason, et al., 2010). However, under high pressure and temperature, the mineralization uptake process can be accelerated by a factor of approximately 10^6 over its unassisted speed in nature (Matter & Keleman, 2009).

Since basalts compose 10% of the Earth's terrestrial surface and much of the ocean floor (Gislason & Oelkers, 2014), estimates for storage potential in basalt formations are high. Gislason & Oelkers (2014) estimate that about 70kg of CO_2 can be stored in one cubic meter of basalt. The global storage potential of peridotite is estimated to exceed 9,000 $GtCO_2$ (Matter & Keleman, 2009). When storage costs are considered for basalt formations on land, the CarbFix project returned an estimated storage cost of \$15/tCO_2e, with storage through the BSCSP pilot project's process expected to cost less than half as much due to the elimination of the cost of pumping water (Gislason & Oelkers, 2014).

Basalt storage is not yet a widely-used storage option, so concerns remain regarding its impact on physical, geochemical, and biogeochemical factors (Matter et al., 2009). Until the carbonation reaction is completed, basalt storage requires the same impermeable cap that is needed for physical storage in saline aquifers or depleted oil and gas wells (Matter et al., 2009). Storage in deep-sea basalts would minimize the leakage risk through gravitational trapping, which prevents degassing at water depths greater than 2,700 meters (Goldberg, et al., 2008). Nonetheless, additional studies are needed to better understand the reaction kinetics, fluid flow rate under aqueous conditions, and the effects of mineralization speed on surrounding fissures and overall rock porosity (Matter et al., 2009, Matter & Keleman, 2009).

Offshore Sediments

Storage of CO_2 in offshore sediments is a practice that is relatively new and has yet to be widely adopted. To date, only a handful of oil and gas companies have investigated offshore sediments as a potential storage location. Offshore Sediment storage is very similar to terrestrial storage sites. However, it is not the same as ocean storage, which will be covered in Chapter 12, and does not suffer the same potential damaging ecological effects that ocean storage might have. Like terrestrial storage sites, offshore sediment storage needs a layer of porous rock, such as sandstone, with a layer of non-porous rock, such as mudstone or shale, to act as a cap to prevent leakage. These conditions are not unheard of in offshore sediment sites. For example, off the coast of New Jersey, there is an old oil field that has been dormant for decades. This offshore oil field alone has the potential to store hundreds of billions of tonnes of CO_2 (Schrag, 2009).

There are a number of benefits to offshore sediment storage that are not shared by terrestrial forms of geologic storage. Two of these benefits stand out. First, if CO_2 is stored in offshore sediments located below 3,000 meters, then the risk of leakage drops dramatically. This is due to the fact that below 3,000 meters, the pressure and temperatures at that depth make CO_2 denser than the surrounding seawater. Therefore, any CO_2 that may leak from the geologic formation will have a difficult time migrating back to the surface (Schrag, 2009).

The second benefit that stands out between offshore sediment storage and terrestrial forms of geologic storage is the pressure management that offshore sediment is able to maintain. This is because, like enhanced oil recovery, when CO_2 is pumped underground, the pressures tends to want to push pore fluids to the surface. In enhanced oil recovery, this is a good thing because it helps to push oil to the surface. However, most non-oil pore fluids tend to be toxic and laced with heavy metals. This is not always the case with pore fluid found in offshore sediment though. These offshore sediment pore fluids tend to share the overall chemistry as the surrounding sea water. Therefore, these pore fluids do not need to be managed in the same way as terrestrial pore fluids. Because these pore fluids can be released back into the ocean, it allows storage sites to extract pore fluid when pressures become too great, thus allowing more CO_2 to be stored (Schrag, 2009).

Economically speaking, any offshore activity tends to be more expensive due to the added complexity of doing things on, or under, the water. However, there is potential for offshore sediment storage to be less expensive compared to other geologic storage methods. The potential savings that come from not having to manage pore fluids, or potentially not having to spend as much on leakage monitoring, could make offshore sediment storage more economically attractive (Schrag, 2009).

Alternative CDR Storage

Although several CDR options including DAC, Terrestrial BECCS, and Aquatic BECCS rely on a form of geologic storage, other CDR options store the captured or sequestered CO_2 in alternative locations that are sometimes more or less energy intensive. Afforestation/reforestation stores the sequestered carbon within the trunk, branches, stems, roots, and even the surrounding soil, similar to soil carbon sequestration (Vashum & Jayakumar, 2012). Soil carbon sequestration typically utilizes plants to sequester and store carbon within the stems, roots, and soil (Bock et al., 2003). Biochar is the carbon-rich char that is left behind when biomass, which stores carbon through photosynthesis, is heated to the point that does not cause complete incineration. This char can then be added to soils or buried underground, where it will decay slowly, releasing the carbon back into the atmosphere over a long period of time (Woolf et al., 2010). Alternatively, through a chemical process accelerated weathering stores the carbon in bicarbonate ions and calcium carbonate solids (NRC, 2015). Lastly, ocean fertilization uses the ocean's natural ability to store carbon in the form of dissolved carbon, as well as, deep carbon sediments (Williamson et al., 2012).

The following two chapters discuss in greater detail two alternative storage options including ocean storage and carbon utilization in the form of enhanced oil recovery. Both of these chapters are formatted similarly to the eight CDR chapters included in this report.

Chapter 12:

Ocean Storage

Ocean Storage

Introduction

Key Findings

- *Ocean Storage is a speculative storage option due to the lack of implementation research regarding the potential adverse effects on aquatic ecosystems.*
- *Ocean Storage has a potential to store 0.55 $GtCO_2e$/year at an approximate cost of \$26/tCO_2e.*
- *However, when all current literature is considered, the estimates range between 0.01 – 0.87 $GtCO_2e$/year at a cost between \$15 - \$266/tCO_2e.*

The world's oceans have the potential to be the largest sink for storing and sequestering carbon. The oceans naturally soak up large quantities of carbon dioxide (CO_2) from the atmosphere through a physio-chemical process until CO_2 levels are at a state of equilibrium between the two. The absorption of CO_2 into the water can take up to a year, and due to ocean currents, this can concentrate CO_2 in different locations. The uptake of CO_2 creates carbonic acid, which can have detrimental effects on aquatic ecosystems (NOAA, 2017).

The idea of direct, or manual, injection of CO_2 has been entertained for several years. However, perceived and potential risks associated with harming the aquatic ecosystems have prevented large-scale studies from taking place. Alternative methods of dumping crop residue into pockets of deep ocean have also been considered. These also have met resistance due to concerns of potential harm to marine life.

The Process of Ocean Storage

Currently, there are many different ways in which CO_2 can be stored deep in the ocean. One of the main ideas is pumping highly compressed CO_2 down to the sea floor or dispersing it in plumes 1,000 – 3,000 meters deep. This CO_2 will slowly migrate back to the surface over a period of hundreds to thousands of years, depending on the depth of storage. However, below 3,000 meters, liquid CO_2 will sink and form a CO_2 lake (Markels et al., 2011). CO_2 can also be put into a solid state, commonly known as dry ice, and be deposited in these areas of deep water (Jones & Young, 2009).

The ocean naturally takes up CO_2 from the atmosphere. However, this only occurs when there is an imbalance between CO_2 levels in the atmosphere and the ocean surface. As the ocean surface absorbs more CO_2, the pH level falls. By directly dissolving CO_2 from smoke stacks into extracted sea water and then neutralizing the pH level with limestone before the water is discharged back into the ocean, allows bicarbonates to form and thus store carbon (Caldeira & Rau, 2000).

The Process of Ocean Storage

The overall process would consist of the following steps:

1. Capturing CO_2 from smoke stacks, or theoretically Direct Air Capture (DAC).
    a. Potentially processing it into a liquid or solid state.
2. Transporting the CO_2, either by pipeline or compressed gas tanks to the ocean.
3. Transporting the CO_2 by tanker or pipeline out to a location offshore with the appropriate depth.
4. Discharging the CO_2 into deep underwater plumes or CO_2 lakes.

According to Metzger & Benford (2001), the overall process of storing CO_2 in the form of dumping crop residue would consist of the following steps:

1. Collecting crop residue from agricultural activity from around the country.
2. Using existing infrastructure to transport crop residue.
3. Loading crop residue onto ships and transporting it off shore to a location with the appropriate depth to prevent decomposition.
4. Off-loading crop residue from the ship directly into the sea.

According to Metzger & Benford (2001), a slightly different, but more simplistic approach to ocean storage is to dump biomass, in the form of farm waste, directly into the deep ocean. Research has suggested that crop residue that is tilled back into the soil does not replace the same amount of nutrients as originally expected. Therefore, collecting this waste and storing it in the deep sea might not be removing natural fertilizers from the land. Some municipalities currently dump organic waste offshore, but it is often in relatively shallow water. This is not effective at storing carbon because the decaying process happens relatively fast, and therefore, CH_4 and CO_2 are released back into the atmosphere. By moving this organic material to a depth below the thermocline, which in the deep oceans stays consistently close to zero degrees Celsius, the decaying process is dramatically slowed down. This method has the advantage of being a low-tech solution to the carbon storage problem, with little to no additional infrastructure or technology needed for immediate implementation.

Carbon Dioxide Storage Potential of Ocean Storage

The projected storage potential of ocean storage is highly dependent on the assumption that this option will not have adverse effects on ocean ecosystems. Therefore, it is assumed that any area of the open ocean that meets the requirements for depth and transportation from land will be available for CO_2 storage. It is estimated that ocean storage has the potential to store between 0.01 – 0.87 $GtCO_2e$/year. The storage potential of ocean storage is listed by source in Figure 12-1.

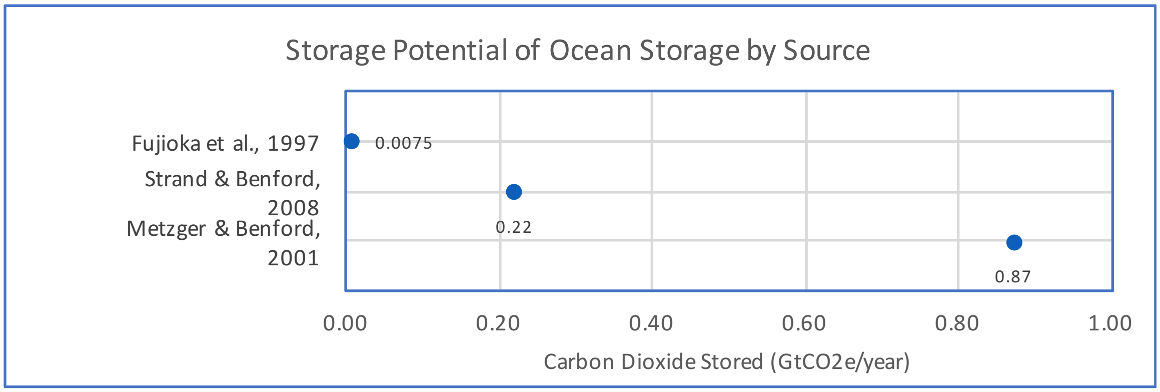

Figure 12-1: Graph of the Storage Potential in Gt of carbon dioxide equivalency per year of ocean storage.

As seen in Figure 12-1, there is a relatively slight variation between the range of estimates from the studies, with a range of 0.01 – 0.87 $GtCO_2e$/year. Due to the limited number of sources found, a quartile analysis was not conducted. However, considering existing infrastructure, and the limited processing needed to dump crop waste directly into the ocean, the average of Strand & Benford's (2008) estimate of 0.22 $GtCO_2e$/year, and Metzger & Benford's (2001) estimate of 0.87 $GtCO_2e$/year, was calculated. Both sources looked at dumping crop residue into the deep oceans, which seems the most plausible option for ocean storage moving into the near future. This gave us an average, and our selected, quantity of 0.55 GtCO2e/year.

Economic Analysis of Ocean Storage

Ocean storage is a speculative storage approach that has been proposed but not yet implemented, nor studied, on a large scale. The numbers provided represent both costs associated with techniques that require little to no technology, to techniques that require extensive technologies that currently do not exist at scale. Depending on collection methods, transportation requirements, additional infrastructure needed, and potential long-term sequestration and storage losses, the cost of ocean storage ranges from \$15-\$266/tCO_2e. Estimated financial costs of ocean storage are listed by source in Figure 12-2.

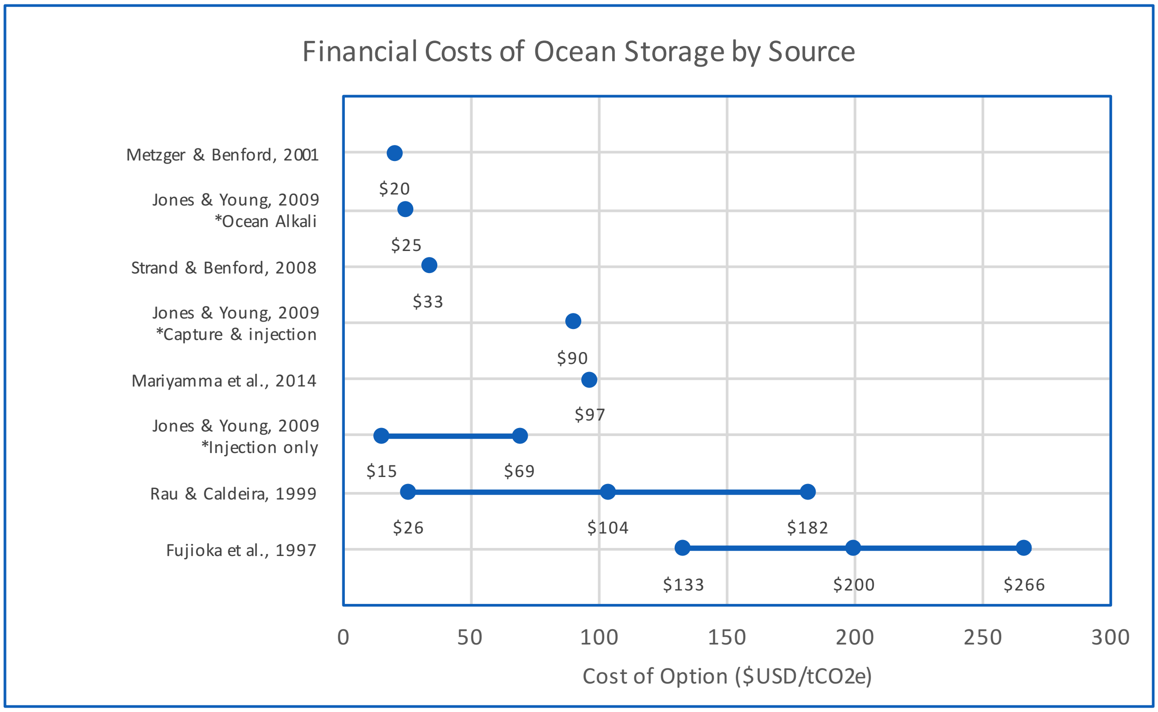

Figure 12-2: Graph of financial costs of ocean storage in 2015 US Dollars per tonne of carbon dioxide equivalency. *Key assumptions made by the original author(s), or this research team, are listed below the source.

As seen in Figure 12-2, there is a significant variation among the estimates, $15 - $266/tCO$_2$e. The wide range in costs for this storage option is due to the fact that there are a number of ways in which carbon can be stored in the ocean. Either through direct injection of CO_2 or dumping crop residue directly into the ocean, each technique requires a different level of engineering and technology. In many cases, new infrastructure will need to be developed to facilitate the transport of CO_2 to the storage site. However, looking at our selected CDR estimates, the only option that could be implemented tomorrow without the addition of new infrastructure or equipment, is the practice of directly dumping crop residue into the ocean. Therefore, we are assuming that dumping crop residue is the most realistic form of ocean storage at this time, and it is estimated that these costs would be around $26/tCO$_2$e.

Geographic Restrictions

Although the oceans are vast and have the potential to store large quantities of CO_2 within the next 100 years, there are still several hurdles to overcome. Currently, the only CO_2 emitting plants that could utilize the ocean for storage are those located near the coastline. Transporting compressed CO_2 by rail or truck would be costly and the infrastructure to transport CO_2 by pipeline does not exist. Additionally, offshore locations suitable for deep ocean storage might be located hundreds of miles from the coast and would require additional shipping costs for the proper storage of CO_2. These geographic restrictions would also apply to the storage of crop residue.

Ocean currents are also a limiting factor of ocean storage. At certain depths, liquid CO_2 will pool or even sink. However, ocean currents could move these pockets of CO_2 into shallower areas where it could potentially start to rise or reach the surface sooner than expected. This might create an inefficient storage situation in specific locations. Well mapped out underwater currents should be in place before implementing ocean storage.

Policy Implications

Dumping waste in the oceans was a common practice for many years leading up to the passing of the Marine Protection, Research, and Sanctuaries Act (MPRSA) in 1972. In international waters, the London Convention and the London Protocol are treaties that govern the protection of marine ecosystems. Currently, the MPRSA law states that there can be no disposal of "persistent inert synthetic or natural materials which may float or remain in suspension in the ocean in such a manner that they may interfere materially" (EPA, 2017). It is unknown if the storage of CO_2 would fall under this restriction because large-scale testing has not yet taken place. The effects on deepwater ecosystems may have unintended consequences that drastically affect fishing stocks. The effects on marine ecosystems would be of concern because the protein diet of a large portion of the world consists almost entirely of fish. Policies and funding should be established to encourage the continued exploration of the deep oceans and the CO_2 storage potential. This would help to determine the effects CO_2 storage would have on marine ecosystems.

Benefits, Challenges, and Tradeoffs

The oceans compose 70% of the earth's surface, with an average depth is 3,800 meters. It is estimated that oceans contain 40,000 GtC, while the storage capacity of the atmosphere and terrestrial biospheres are 750 GtC and 2,200 GtC respectively (Sabine et al., 2004). It is also estimated that 80% of the excess CO_2 will be sequestered naturally into the ocean until CO_2 levels between the atmosphere and the oceans are equalized. However, this is expected to take a very long time, and the time horizon increases with the continued uptick in global CO_2 emissions (Mariyamma et al., 2014). Even though the oceans will be absorbing the CO_2, this creates its own set of problems.

When salt water absorbs CO_2, it creates carbonic acid, which lowers the surface water's pH level. This effects any organism with a carbonate shell by making the shell weaker (Markels et al., 2011). The pH level of deep water will also drop, however, the temperatures and pressures at those levels have different effects on liquid CO_2 than the temperatures and pressures at the surface. Little is known about the effects of CO_2 injection on deep-sea organisms.

The concept of dumping crop residue into deep pockets of the ocean has its own benefits, challenges, and tradeoffs. It is estimated that the equivalent of 0.87 $GtCO_2$/year could be stored by adopting this method. This would have waste from agricultural activity shipped to the coasts and then transported out to a deep sea location where it would be dumped. At the deep sea temperatures and pressures, decomposition is dramatically slowed down, thus storing the embedded carbon within the biomass (Metzger & Benford, 2001). This could all be done using existing equipment, infrastructure, and technology. It has a low energy input because there is little to no processing of the crop residue, other than transportation. This form of CO_2 storage would create a large amount of low-skilled, but well-paying jobs, and could be implemented immediately.

Deep sea ocean storage can contribute to solving our CO_2 storage needs. However, it also has the potential to have a major biological impact, which could potentially impact global food chains, making it risky to implement without thorough research. Additionally, much of the CO_2 will inevitability migrate back to the surface and back into the atmosphere. This has caused it to gain little public acceptance, and therefore very little large-scale research has been done on this form of CO_2 storage.

Further Research

Further research is needed regarding deep ocean ecosystems and how they affect the other ecosystems which people rely on. Continued research is needed on detailed mapping of ocean currents. Additionally, more research is needed to see how large quantities of CO_2 stored underwater will behave through scaled-up pilot tests. A storage method like ocean storage would be hard to reverse once implemented. Therefore, any impacts associated with this process should be reviewed to minimize unintended consequences.

Conclusion

In conclusion, it is estimated that ocean storage could store about 0.55 $GtCO_2e$/year at an approximate cost of \$26/tCO_2e. When considering all the estimates from the literature, ocean storage could be implemented at a cost between \$15 - \$266/tCO_2e with the ability to store 0.01 – 0.87 $GtCO_2e$/year. Further research regarding the effects of large quantities of CO_2 on deep-sea marine life, as well as, the subsequent effect on the greater health of the oceans as a whole, is necessary before mass implementation.

Chapter 13:

Carbon Utilization

Carbon Utilization

Introduction

Key Findings

- *Enhanced Oil Recovery (EOR) is considered an established storage option due to commercial scale operations currently in existence.*
- *EOR has the potential to store 65 $GtCO_2e$ at an approximate price of \$40/tCO_2e.*
- *However, when all current literature is considered, the estimates range between 0.05 – 370 $GtCO_2e$ at a price between \$17 - \$50/tCO_2e.*

Throughout this report, carbon dioxide (CO_2) is captured through various methods, three of those, bioenergy with carbon capture and storage, aquatic bioenergy with carbon capture and storage, and direct air capture produce concentrated streams of CO_2. The prevailing approach to storing this CO_2 is to inject it into geologic storage locations where it will stay for, theoretically, thousands of years. Another option is available, carbon utilization. Carbon utilization is the idea that the CO_2 which is collected through carbon dioxide removal (CDR) options does not have to be a passive entity to be stored. Concentrated CO_2 is a versatile product and can have many productive uses. Common uses of CO_2 include cement, carbonated beverages, fuels like syngas, and in enhanced oil recovery (Lackner et al., 2012). Figure 13-1 provides a visual summary of different uses of CO_2.

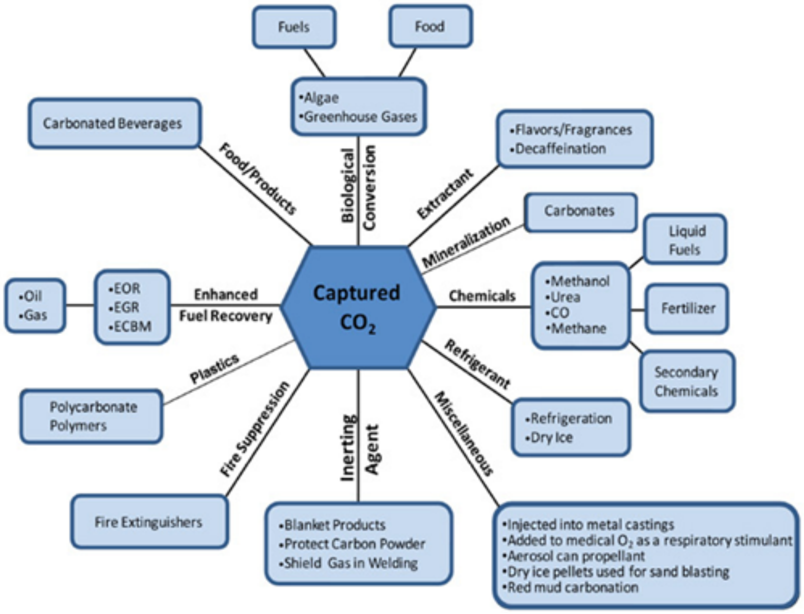

Figure 13-1: The processes and products in which captured CO_2 can be used. Image from NETL, 2017.

Enhanced Oil Recovery (EOR) Process

Figure 13-1 shows CO_2 can be used in various industrial and commercial ways, besides using captured CO_2 in enhanced oil recovery (EOR), plastics, or concrete, the majority of carbon utilization options do not provide long-term storage and the captured CO_2 would quickly return to the atmosphere. As EOR has been conducted by the oil industry for decades, the rest of this chapter shall focus on EOR.

EOR is a process that injects CO_2 into oil wells to increase well production. There are 114 EOR projects in the United States (Kuuskra et al., 2011). EOR increases oil production by 10-15% (Benson et al., 2012) equaling roughly 6% of total US crude oil production (Kuuskraa et al., 2013). While oil companies have used CO_2 from natural sources, in the future, CO_2 could be delivered from anthropogenic sources since CO_2 is the limiting resource in the EOR process (Kuuskra et al., 2011).

The EOR process begins with the creation of the well and the extraction of oil from the well. Once the production of the well is showing signs of slowing, a second recovery is performed and the well is flooded with water (Lake et al., 2014). A third recovery is performed when CO_2 is injected into the well and displaces oil. This releases the oil and brings it to the surface along with some of the CO_2. Injecting 1 tonne of CO_2 releases 2.5 barrels of oil (Kuuskraa et al., 2013). Between 30% and 60% of the CO_2 returns to the surface with the oil (Benson et al., 2012). This CO_2 is separated from the oil and re-injected. Figure 13-2 illustrates the EOR injection process.

Steps in the EOR Process

The overall EOR process would consist of the following steps

1. Oil extraction process, digging the well and recovering oil.
2. Once production slows, a water flood is performed to extract more oil.
3. After flooding, a third recovery using CO_2 is performed.
4. CO_2 is injected into the well, releasing oil.
5. Oil is extracted and a portion of the CO_2 comes up with the oil.
6. The extracted CO_2 is separated from the oil and re-injected.
7. The CO_2 is permanently stored in the oil field.

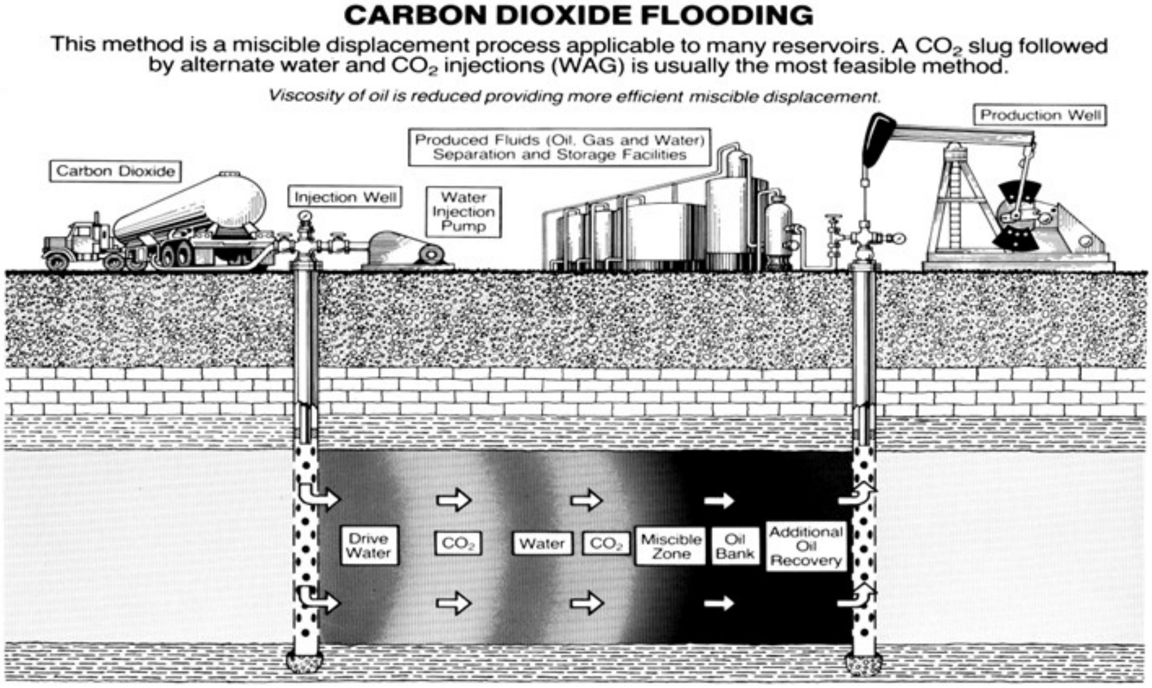

Figure 13-2: Illustration of EOR injection process. Image from Lindley, 2001.

Carbon Dioxide Storage Potential of Enhanced Oil Recovery (EOR)

The storage potential for EOR is reported differently than the eight CDR options, as well as the other storage-only option, in that the total available storage potential is given, besides the 2010 actual injection numbers presented in Benson et al. 2012 and Kuuskraa et al., 2013. As all the storage potential is available, reporting an annual number would not be as informative as the total potential for EOR. The estimates of total EOR storage potential varies greatly and the majority of this variance is due to the time and scope of the study. It is estimated that the sequestration rates span from 0.05 to 370 GtCO$_2$e. The CO$_2$ storage potential of BECCS is listed by source in Figure 13-3.

Though not specifically stated, Benson's (2012) paper appears to report just geologic supplied CO$_2$ while Kuuskraa's (2013) number adds anthropogenic supplied CO$_2$. This assumption is made based off table 3 in Kuuskraa's (2013) paper where they breakdown the CO$_2$ stored in 2010 into 49 MtCO$_2$ geologically and 13 MtCO$_2$ anthropogenically. The other estimates on the lower end of the range are for the Western Canada Sedimentary Basin. This region is of significance due to the Boundary Dam Power Station that began sequestering CO$_2$ as of October 2014. Bachu's (2004) and Shaw's (2002) estimates are highly related since the authors worked on both studies. Their 2002 low estimate is based on their breakthrough scenario, the medium estimate is based on a hydrocarbon pore volume of 50% and the high value is based on a hydrocarbon pore volume of 100% (Shaw et al., 2002). Two years later, they revised their estimates to a narrower range. This narrower range may be attributed to the discussion of the aquifer effect, which reduces capacity, and by increasing the number of EOR favorable oil pools from 4,470 to 4,767 (Bachu et al., 2004). Another region-specific study was performed by Middleton (2013) who analyzed 29 reservoirs in Oklahoma, Texas, and Louisiana (Middleton, 2013).

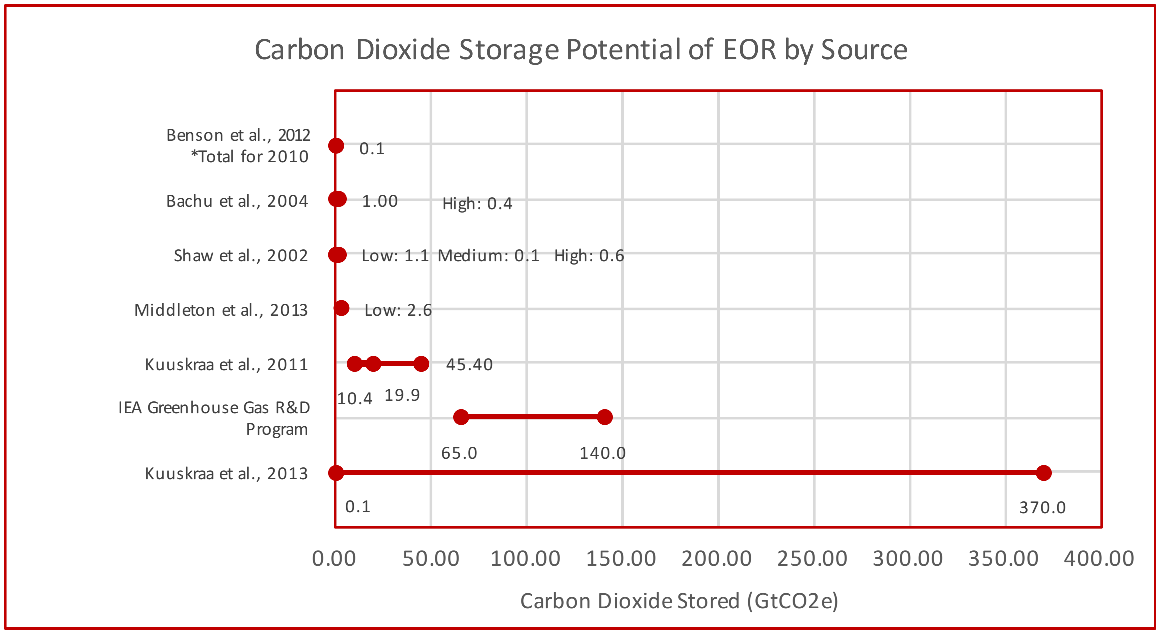

Figure 13-3: Graph of carbon dioxide storage potential in Gt of carbon dioxide equivalency of EOR.

The National Energy Technology Laboratory (NETL) conducted a study, whose lead author is Kuuskraa, looking at next generation EOR practices and came up with the middle and high estimates. The middle estimate represents what is economically feasible and the high estimate represents what is technologically feasible. Even though this report focused on next generation EOR practices, they include an estimate of the storage potential of our current state-of-the-art EOR technology, which represents the low end of the range.

The highest two estimate sources cover the entire world. The IEA (2009) estimate assumed current EOR technologies and used the United States Geological Services Petroleum Assessment and US basin screening to convert to world basins (IEA, 2009). The high end of the range is for world storage potential while the low end of the range limits the distance between CO_2 sources and the well that the CO_2 is to be injected to 800 km.

Kuuskraa's (2013) high-end estimate is more than 2.5 times bigger than the next closest estimate. This is due to a couple of factors. Kuuskraa (2013) uses next generation EOR technologies, while the IEA (2009) uses current EOR technologies. The estimate also includes the potential of discovered but also undiscovered fields. The paper assumes that next generation technology is able to infiltrate residual oil zones.

Due to its use of current EOR technology and entire world scope, the IEA 2009 article was selected for comparison purposes. Of the two estimates provided in that paper, 65 $GtCO_2$ was selected as a more realistic estimate as it considers the distance the captured CO_2 would have to travel and limits it to 800 km.

Economic Analysis of Enhanced Oil Recovery

Unlike the previous chapters, carbon utilization provides a means of selling the CO_2 that has been captured. Academic work is limited in providing prices and obtaining prices paid by industry is challenging. A general rule of thumb is an EOR operator would pay 2% of the price of a barrel of Western Texas Intermediate (WTI) oil for one million cubic feet of CO_2 (Middleton, 2013). The price of CO_2 for EOR ranges from $17 to $50/$tCO_2$. Estimated financial costs of EOR are listed by source in Figure 13-4.

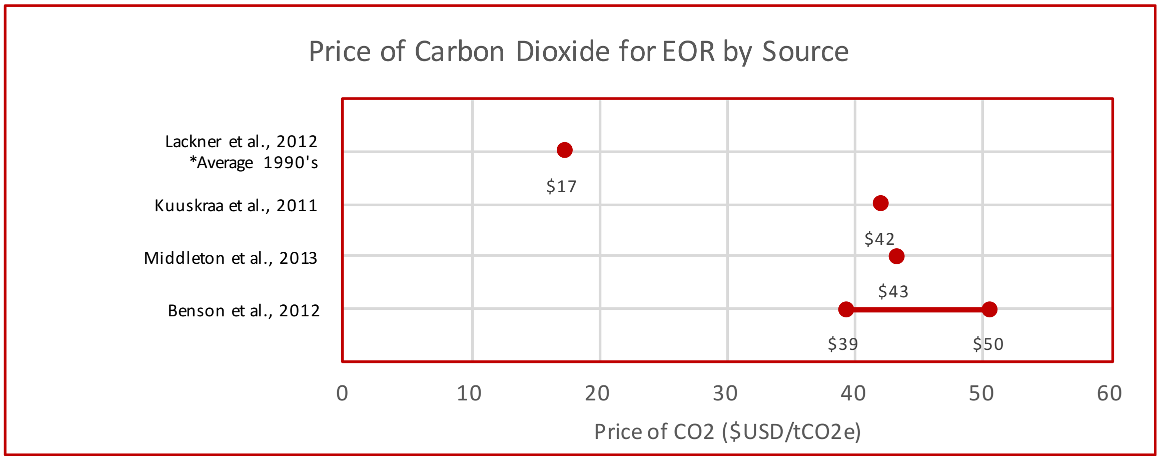

Figure 13-4: Graph of price per tonne of carbon dioxide equivalency used in EOR in 2015 US Dollars.

The lowest price in the range came from Lackner (2012) who cited the average price of a tonne of CO_2 in the 1990s (Lackner et al., 2012). All other prices are fairly consistent with one another. The NETL report used a per barrel price of $85 to calculate a price of $40/$tCO_2$ (before conversion to 2015 USD), using a rate of 2.5% of a WTI barrel of oil (Kuuskra et al., 2011). Middleton (2013) used a barrel price of \$81.08 and calculated a price of \$42.23/tCO_2, however, Middleton chose to use a price of \$40/tCO_2e (before conversion to 2015 USD), explaining that other academic work was using that price. Benson (2012) stated the economics for EOR are difficult due to the variability of oil prices (Benson et al., 2012). The average price of a barrel of WTI for 2016 \$43.33 (EIA, 2017). Prices estimated using this average would be significantly lower than the estimates in most of the papers reviewed (EIA, 2017).

Since the NETL report, Middleton's article and others cite \$40/tCO_2 as the price of a tonne of CO_2 for EOR purposes, that estimate will be used for comparison purposes with other CDR and storage only options.

Geographic Restrictions

There are two factors that contribute to the geographic restrictions for EOR. The first is the availability of CO_2. There must be a source of CO_2 in a relatively close distance or the cost will become prohibitively expensive. The IEA (2009) placed an 800 km distance limitation to calculate feasible storage potential. The oil wells themselves are the second geographic restriction. They are already constructed so they will determine where EOR can happen. In the United States, 31 states produce oil and Texas, Alaska, California, Louisiana, and Oklahoma are the largest producers (Department of Energy, 2013).

Policy Implication

One of the biggest policy concerns with EOR is public acceptance. There are concerns over the safety of injecting CO_2 underground for storage. The safety concerns are regarding leakage and the impacts on human health and the environment. Public policies need to ensure that the injected CO_2 does not pose any harm and assuage public concern. While EOR has been underway for decades without any major safety issues, the amount of CO_2 that may be injected in the future, up to 370 GtCO_2, from 50 MtCO_2 in 2010, may pose new issues.

To enable large-scale EOR capacities, CO_2 needs to be able to be transported easily. The lack of available CO_2 has limited the growth of EOR (Benson et al., 2012). To facilitate this transportation, the United States would need a pipeline system greater than the scale of its current oil pipeline system (Middleton, 2013). New oil pipelines have become a hot-button issue for environmentalists and these CO_2 pipelines may face intense public outcry particularly because they will be seen as enabling additional oil extraction and prolonging fossil fuel use.

Benefits, Challenges, and Tradeoffs

The biggest benefit for carbon utilization and EOR is the existence of a market for CO_2 (Lake et al., 2014). It can provide a financial incentive for industry to capture CO_2. The price paid by EOR operators is contingent upon the price of a barrel of WTI and the current low price of oil does not provide sufficient incentive for EOR to be commercially viable. If prices in the future provide that incentive, EOR can offset some of the additional costs to capture carbon. EOR can help jump start carbon capture (Middleton, 2013).

Beyond creating revenue and lowering net capture costs, EOR is cost effective because significant costs have already been incurred to create the injection wells. These sunk costs allow EOR to be implemented with minimal capital costs. As CO_2 injection has been performed for decades, there is already an amassed knowledge of the process along with long-term storage and monitoring. The IPCC Special report on CO_2 Capture and Storage stated that a well-designed EOR project could store 99% of its CO_2 for one thousand years (Metz et al., 2005). There have not been any reported instances of CO_2 leakage from the EOR project sites. Other considerations like regulations, mineral rights, and subsurface data has already been addressed and further eases the burden of implementation (Kuuskraa et al., 2011).

While EOR can be integrated into CDR options, it can also help facilitate CCS, which at best is a carbon neutral emission option, if naturally occurring CO_2 is used then EOR results in increased carbon emissions. Hence, EOR is not strictly positive or negative; it depends on how it's used. This may be a challenge for the public to understand EOR and for policy makers to make proper decisions surrounding EOR.

There has been controversy over EOR's role in seismic activity. The National Research Council (2013) acknowledged that the injection of CO_2 could contribute to seismic activity especially when the injection causes a fluid imbalance. In the Cogdell oil field in Texas, CO_2 has been injected since 2004 and from 2006 to 2011 18 magnitude 3 or higher earthquakes have been felt (Gan et al., 2013). Gan (2013) was the first academic article to link EOR and seismic activity. Zoback (2012) indicated that as larger amounts of CO_2 are injected there is an increased likelihood of seismic activity. However, the reduced pressure from the extraction of oil and the subsequent input of CO_2 is less of a concern (Zoback et al., 2012). To prevent seismic activity and reduce the risk of leakage, sites need to be chosen that are highly porous and permeable (Zoback et al., 2012). In the end, the National

Research Council concluded there was no connection between seismic activity and EOR (NRC, 2013).

Future Research

Next generation EOR promises to increase the storage potential of CO_2 to include residual oil zones and offshore sites. As next generation EOR allows for more CO_2 injection and as the interest in EOR grows, the concerns for environmental and public health and safety will rise. Future research should better understand the impacts of large-scale implementation of EOR, efficient CO_2 transportation, and continue to gather long-term data on existing EOR storage sites. Much can be learned from EOR in the context of geologic storage and future research should translate it to other storage solutions.

Conclusion

Enhanced oil recovery is one of many ways that captured CO_2 can be used in a commercial process. EOR was the focus of this chapter due to its permanent storage component. As CO_2 becomes a commodity, the EOR process will become economically valuable. Even with the 2% rule of thumb, the literature provides a range of \$17 to \$50/tCO_2e. The CO_2 injected has proven to stay in the well as shown through decades of injection by EOR operators with no leakage (Benson et al., 2006). The estimated range of storage potential goes from the 2010 storage number of 50 MtCO_2e up to a world average of 370 GtCO_2e. While EOR provides a means to store CO_2 and create revenue to offset costs of capture, questions remain about the safety of such a process, especially when considering an increase of EOR activity in the future, and the impact on climate change.

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