U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Bioenergy's Role in Soil Carbon Storage

Decarbonizing Transportation, Agriculture, and Industrial Sectors

Workshop Summary Report | March 2023

Disclaimer

Foreword

The mission of U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) is to accelerate the research, development, demonstration, and deployment of technologies and solutions to equitably transition America to net-zero greenhouse gas emissions economywide by no later than 2050, and to ensure the clean energy economy benefits all Americans, creating good-paying jobs for the American people—especially workers and communities impacted by the energy transition and those historically underserved by the energy system and overburdened by pollution.

EERE's Bioenergy Technologies Office (BETO) supports research, development, and demonstration to enable the sustainable use of domestic biomass and waste resources for the production of biofuels and bioproducts. Focuses of the program include technologies and processes that transform renewable carbon sources into conversion-ready feedstocks.

This report summarizes the input received from attendees of the public workshop sponsored by BETO on March 28–29, 2022. A record of the workshop agenda and presentations is available online: https://www.energy.gov/eere/bioenergy/events/workshop-bioenergys-role-soil-carbon-storage.

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Acknowledgments

This summary report was prepared by Mark Elless, Charlotte Levy, and Anne Otwell, with support and contributions from Chenlin Li, Elizabeth Burrows, Art Wiselogel, Brianna Farber, Alexander Jansen, Camryn Sorg, Richard Coaxum, and Nichole Fitzgerald. Workshop conceptualization and planning was led by Charlotte Levy and Mark Elless, with expertise and support from Elizabeth Burrows, Chenlin Li, Art Wiselogel, and Richard Coaxum. Melissa Ladd of BCS is thanked for her facilitation planning, including group discussion process, questions, virtual format, and training the team of breakout session moderators. Stacey Young of The Building People is thanked for her expert event logistics and support. Nichole Fitzgerald, program lead for BETO's Renewable Carbon Resources program, and Valerie Reed, director of BETO, contributed higher-level guidance throughout workshop preparation. Much gratitude is also extended to the BETO communications team, particularly Sheila Dillard, Caroline Arkesteyn, and Justin Rickard. We gratefully acknowledge the team of moderators, co-moderators, and scribes who guided participants in each breakout session discussion (Table 1).

Table 1. Breakout Session Leads

Session	Moderator	Co-Moderator and Scribe
Agricultural Residues, Session 1	Mark Elless	Alexander Jansen
Agricultural Residues, Session 2	Chenlin Li	Camryn Sorg
Dedicated Bioenergy Crops, Session 1	Elizabeth Burrows	Anne Otwell
Dedicated Bioenergy Crops, Session 2	Richard Coaxum	Brianna Farber
Forest Materials/Residues, Session 1	Art Wiselogel	Melissa Ladd
Forest Materials/Residues, Session 2	Charlotte Levy	Ian Rowe

The authors would like to sincerely thank the workshop participants for their contributions, which provided input for this publication. The full list of individuals who registered for the workshop is provided in Appendix B. Particular thanks go to the workshop speakers, who contributed their time and expertise to help inform and shape the workshop discussions (Table

2). Thanks also go to workshop participants who contributed 3 × 5 lightning talks to the workshop (Table 3).

Table 2. Workshop Speakers, Presented Alphabetically

Speaker	Affiliation
Ronald Amundson	University of California, Berkeley
Asmeret Asefaw Berhe	University of California, Merced
David Babson	DOE, Advanced Research Projects Agency–Energy
Francesca Cotrufo	Colorado State University
John Field	Oak Ridge National Laboratory
Kaiyu Guan	University of Illinois at Urbana-Champaign
Kirsten Hofmockel	Pacific Northwest National Laboratory
Elise Hung	Rice University
Virginia Jin	U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS)
Sandeep Kumar	USDA, National Institute of Food and Agriculture
Hoyoung Kwon	Argonne National Laboratory
David Laird	Iowa State University
Rattan Lal	Director, Rattan Lal Center for Carbon Management and Sequestration, Ohio State University
Mark Liebig	USDA-ARS
Cristine Morgan	Soil Health Institute
Vance Owens	USDA, National Institute of Food and Agriculture
Keith Paustian	Colorado State University
Jennifer Pett-Ridge	Lawrence Livermore National Laboratory
Ghasideh Pourhashem	Genomatica
Wei Ren	University of Kentucky
Tom Richard	Penn State University
Michael Robotham	USDA, Natural Resources Conservation Service
Carlos Rodriguez Franco	USDA, Forest Service
Brandi Schottel	National Science Foundation
Peter Vadas	USDA-ARS
Tim Volk	State University of New York College of Environmental Science and Forestry
Jingxin Wang	West Virginia University

Boris Wawrik	DOE, Office of Science, Office of Biological and Environmental Research

Table 3. Stakeholder Lightning Talks, Presented Alphabetically

Speaker	Affiliation
Chris Benedict	Washington State University
Ben Brown	Arva Intelligence
Zac Freedman	University of Wisconsin-Madison
Marie Kroeger	Los Alamos National Laboratory
Umakant Mishra	Sandia National Laboratories
Jorge Mazza Rodrigues	University of California, Davis
Allen Torbert	USDA-ARS
Thea Whitman	University of Wisconsin-Madison
Mary Belle Zook	Indigenous Food and Agriculture Initiative

List of Acronyms

ARPA-E	Advanced Research Projects Agency–Energy
ARS	Agricultural Research Service
BECCS	bioenergy with carbon capture and storage
BETO	Bioenergy Technologies Office
CI	carbon intensity
CO_2	carbon dioxide
DOE	U.S. Department of Energy
GHG	greenhouse gas
LCA	life cycle analysis
LUC	land use change
MAOM	mineral-associated organic matter
NSF	National Science Foundation
POM	particulate organic matter
R&D	Research and Development
SMARTFARM	Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management
SOC	soil organic carbon
USDA	U.S. Department of Agriculture

Executive Summary

On March 28–29, 2022, the U.S. Department of Energy's (DOE) Bioenergy Technologies Office (BETO) hosted the public virtual workshop "Bioenergy's Role in Soil Carbon Storage." Given the recent emphasis of the Biden administration on decarbonizing transportation, agriculture, and industrial sectors of the U.S. economy, this workshop examined how decarbonization through enhanced soil carbon storage while growing bioenergy crops is possible by discussing challenges and opportunities that affect soil carbon levels. Stakeholders representing academia, industry, the farming community, agricultural and forestry sectors, municipalities, and federal agencies involved in soil carbon storage participated in this workshop. A series of keynote presentations, plenary presentations, and stakeholder input sessions provided opportunities for sharing knowledge and identifying research and development (R&D) needs for future advances in soil carbon storage in relation to bioenergy crops. This document provides an overview of the content discussed in the presentations, as well as a summary of the stakeholder input received during the session discussions.

Climate-smart production practices, such as omitting tillage, deploying cover crops, and applying biochar, are becoming more popular mechanisms for enhancing soil carbon storage. When these practices are applied in concert with the growing of deep-rooting, perennial, bioenergy crops that minimize inputs, larger reductions in carbon intensities can be realized through enhanced soil carbon storage compared to traditional crops. The permanence of soil carbon storage can be affected by land management, so factors that affect soil carbon stability need to be assessed and characterized to preserve the benefits of soil carbon storage.

This virtual workshop solicited input on a variety of topics: edaphic factors affecting soil carbon stability; management practices affecting soil carbon, such as biochar application; and the effect of bioenergy crops on soil carbon storage. The keynote presentation speakers provided an overview of the importance of soil carbon to combat increasing atmospheric carbon levels due to fossil fuel use and soil degradation. The need for negative-emission agriculture—which reduces carbon emissions from farm operations and sequesters the carbon in soils, trees, and wetlands to mitigate climate change—was emphasized. Overall, a key conclusion of the workshop is that R&D is needed to better understand how to leverage soil carbon storage to produce lower-carbon-intensity biofuels.

There were six technical sessions:

1. Mechanisms of Soil Carbon Storage
2. Management Strategies to Optimize Soil Carbon Storage
3. Agricultural Management Practices to Optimize Soil Carbon Storage
4. Forest Management Practices to Optimize Soil Carbon Storage
5. Research and Development Needed to Support Policy for Soil Carbon Storage in Bioenergy
6. Tools for Decision Making in Bioenergy and Soil Carbon Storage.

Invited presentations, lightning talks, and breakout sessions, as well as the diverse stakeholder perspectives gathered in the breakout sessions, provided workshop participants with a shared understanding of the state of soil carbon levels as affected by management practices and edaphic factors. Group discussion further enabled cross-pollination of ideas.

Workshop participants supported the concept that soil carbon storage and biofuel production can work synergistically. Increasing soil carbon storage improves the health of the soil and can result in higher-yielding bioenergy crops, which in turn can produce lower-carbon-intensity biofuels. Many areas of R&D were identified during the workshop, and participants emphasized the need for long-term studies that give reliable field data. Application of soil amendments such as biochar could potentially lead to long-term soil benefits, but considerable applied R&D is necessary to fully correlate biochar properties and performance. The information and feedback gathered at this workshop will help DOE address the most critical barriers tto reducing carbon intensity of feedstocks for biofuels and bioproducts though enhanced storage of soil carbon. BETO would like to thank all of the participants for their valuable input.

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Introduction

Overview

Our economy is built on carbon—from the fuels we rely upon to the products we use every day that improve our lives. In the United States, we have become accustomed to the way of life that carbon has allowed. This includes the fuel powering our personal vehicles and the packaging on our foods that keep them safe for us to consume.

Unfortunately, most of the carbon in our fuels and products is from petroleum sources—sources that result in severe environmental consequences, including high greenhouse gas (GHG) emissions and correspondingly high carbon intensities (CIs) associated with its extraction, refining, and use. Alternatively, biogenic carbon (i.e., carbon from biomass) represents an opportunity whereby this captured carbon from photosynthesis can produce fuels with much lower GHG emissions and CIs. In addition, harvesting of the biomass has a much lower carbon footprint than petroleum extraction, thereby helping to decarbonize our economy from petroleum sources of carbon.

Climate-smart production practices can be adopted to reduce the carbon intensity associated with biomass growth for biofuels. The U.S. Department of Agriculture (USDA) defines climate-smart production practices as "agricultural and forestry practices or combinations of practices, and/or practice enhancements that provide GHG benefits and/or carbon sequestration."[1] Some of these practices, such as growing cover crops, using low-till or no-till practices versus conventional tillage, and applying soil amendments such as biochar, seek to preserve or enhance the organic carbon level in soils, thereby mitigating GHG emissions from agricultural lands and even serving as a carbon sink (Figure 1).

This workshop was therefore seeking to examine the nexus between climate-smart production practices, soil carbon levels, and biofuel production from feedstocks with lower CIs than conventionally grown feedstocks, particularly from agricultural and silvicultural residues and energy crops. When successful, fuels and products made from these low-CI feedstocks that displace their petroleum-based counterparts will help to decarbonize the aviation and industrial sectors, thereby addressing the need for sustainable alternatives for liquid fuels and products to reduce the carbon footprint of these sectors.

[1] USDA. 2022. "Partnerships for Climate-Smart Commodities." usda-partnerships-climate-smart-factsheet-22.pdf

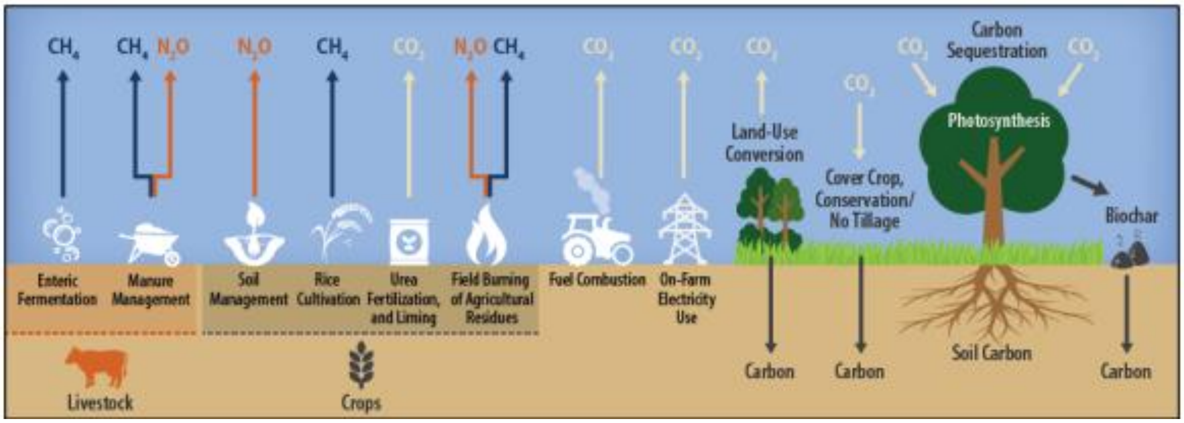

Figure 1. Examples of GHG emission sources and sinks from agricultural activities. Enteric fermentation refers to digestive processes in ruminant animals, which result in GHG emissions.[2]

Workshop Objectives

The objectives of this workshop were to identify soil carbon storage R&D needs as they pertain to bioenergy. To gather this information, a variety of experts in relevant fields gave technical presentations, and participants attended interactive breakout sessions. There were two plenary talks and a session "Highlights from Previous Federal Programs on Soil Carbon and Current Agency Perspectives/Directions" on the main stage. There were six technical sessions: (1) Mechanisms of Soil Carbon Storage, (2) Management Strategies to Optimize Soil Carbon Storage, (3) Agricultural Management Practices to Optimize Soil Carbon Storage, (4) Forest Management Practices to Optimize Soil Carbon Storage, (5) Research and Development Needed to Support Policy for Soil Carbon Storage in Bioenergy, and (6) Tools for Decision Making in Bioenergy and Soil Carbon Storage. Sessions 1 and 2, 3 and 4, and 5 and 6 ran concurrently. Additionally, researchers were offered an opportunity to present their work in a 5-minute lightning talk so their findings could also help inform stakeholder input. These technical presentations set the stage for the breakout discussions and ensured that participants were working from the same common framework. Speaker summaries for all talks are provided starting on page 4 of this report, and slides submitted by speakers are linked in the talk titles.

Targeted questions were asked during the breakout sessions to gather stakeholder input and to help the U.S. Department of Energy's (DOE) Bioenergy Technologies Office (BETO) assess the current state of technology and future R&D needs. Breakouts were organized according to feedstock: (1) agricultural residues, (2) dedicated bioenergy crops, and (3) forest materials/residues. Appendix C summarizes feedback gathered from the breakout sessions.

Alignment with BETO's Mission and Priorities

This workshop was organized in accordance with BETO's mission to decarbonize the transportation and industrial sectors by providing sustainable biomass to produce biofuels (such

[2] Congressional Research Service. 2022. "Greenhouse Gas Emissions and Sinks in U.S. Agriculture." https://sgp.fas.org/crs/misc/IF11404.pdf

as sustainable aviation fuel) and bioproducts. To help meet its mission, BETO is working toward accomplishing the following goals to enhance soil carbon storage for bioenergy applications:

1. Maximize soil carbon sequestration by developing healthy, productive soils and regenerating distressed soil. This includes developing tools and strategies to quantify (e.g., sensors) and improve soil carbon sequestration and ecosystem services, thereby producing biofuels with lower carbon intensities.
2. Identify opportunities to improve carbon sequestration in plants and soil microbiomes through enhanced agronomic and agricultural practices (e.g., biochar application, cover crops, enhanced-efficiency fertilizers) with fewer inputs and greater nutrient and water use efficiency.

While these goals are aligned more with decarbonizing the agricultural sector, BETO recognizes that decarbonization of the transportation and industrial sectors is intrinsically linked, as reduced-CI feedstocks will lower the carbon intensity of the resulting biofuels and bioproducts.

Workshop Participation

Over 650 people registered for the workshop, with 454 total unique attendees. Actual attendance was 416 on Monday, March 28, and 310 on Tuesday, March 29. The majority of workshop attendees came from either academia, national labs, or small businesses (Figure 2).

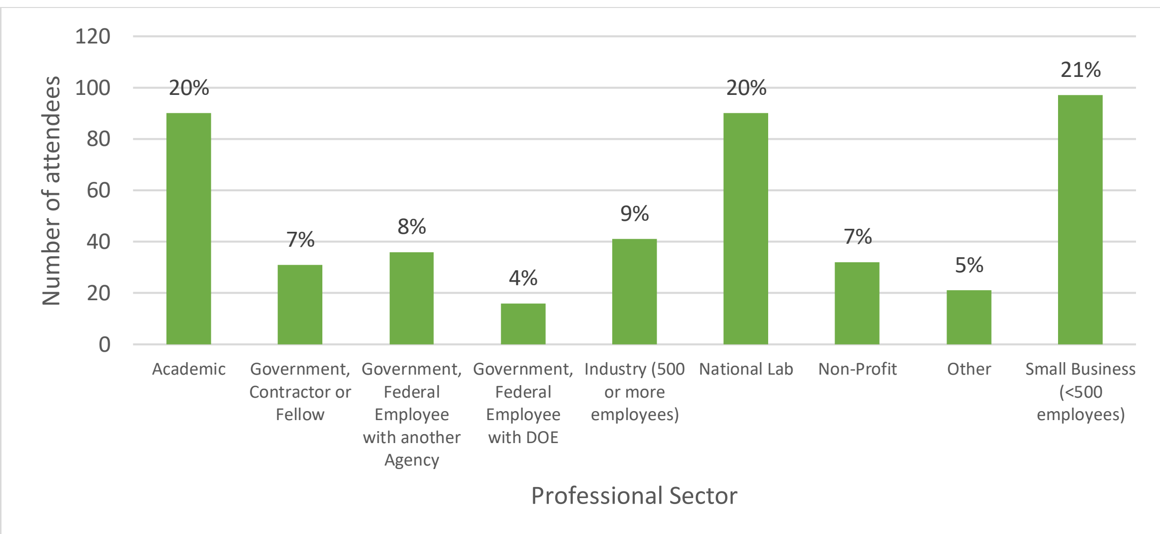

Figure 2. Self-identified affiliation of workshop participants

When asked to self-report on their background, more than half of participants reported having experience in feedstocks (Table 4). Approximately half had experience in soil amendments, soil carbon R&D, and climate-smart agriculture practices. About a third had experience in soil carbon measurement and analysis and life cycle analysis of soil carbon.

Table 4. Summary of Stakeholders' Experience in Soil Carbon

Criterion: "areas in which you have the most experience" sorted by sum. 5 selections of 9 items. Ratings submitted: 139. Total selections: 496. Abstentions permitted.	
Experience Area	**Number of Participants**
Feedstocks (soil carbon sequestration or standard practices)	93
Climate-smart agricultural practices	74
Soil amendments (biochar, compost, silicate rock weathering)	68
Soil carbon R&D (field trials, sequestration)	61
Other	50
Soil carbon measurement/analysis	49
Life cycle analysis of soil carbon	42
Policy affecting soil carbon	32
Edaphic factors affecting soil carbon levels or stability	27

Summary of Invited Talks

Plenary Talks

Negative-Emission Farming and Soil Carbon Sequestration

Professor Rattan Lal, Director, Rattan Lal Center for Carbon Management and Sequestration, Ohio State University, presented on soil carbon sequestration as a mechanism for reducing net emissions. Professor Lal showed that there have been large increases in atmospheric carbon due to fossil fuel use, land use conversion, and agriculture. He showed that soil degradation is a significant source of GHG emissions. Carbon sequestration can store carbon in land and protect against losses through land degradation. Negative-emission agriculture, which reduces carbon emissions from farm operations and sequesters the carbon in soils, trees, and wetlands, is necessary for both adaptation and mitigation of anthropogenic climate change. Professor Lal introduced the concept of regenerative agriculture, which seeks to transfer the carbon dioxide (CO_2) in the atmosphere back to the terrestrial biosphere. Regenerative agriculture includes practices such as minimizing soil disturbance by conservation agriculture, continuous soil cover, integrated nutrient management, use of cover crops, and crop rotations.

Professor Lal's presentation generated a rich discussion. One question centered on how much residue can be removed while maintaining soil health. He stated that optimal residue removal is site specific. With some soils, especially those prone to erosion, only a small portion (<20%) can be removed to maintain soil health. Other soils can have larger removal rates and still maintain soil health. Overall, Professor Lal felt that we should return as much residue to the soil as possible. Another question was whether carbon credits are needed to promote regenerative agricultural systems. Professor Lal responded that it is better to pay the farmer for ecosystem services that they create rather than implement a carbon credit pathway. He was then asked about how to deal with critics of regenerative agriculture. Professor Lal responded that we need to convince farmers to employ agricultural practices that have been shown to produce benefits, but they are more likely to listen if they will be paid for the ecosystem services they provide.

The Role of Soil Carbon Sequestration in Reducing the Carbon Intensity of Bioenergy Systems

Professor Asmeret Asefaw Berhe, University of California, Merced, presented on how bioenergy relates to soil carbon sequestration. Dr. Berhe emphasized that limiting global warming to 1.5°C requires not only a reduction in emissions, but also implementing climate-smart practices that result in negative emissions. Professor Berhe showed recently published data from her group's work on the propensities of various management strategies (i.e., forests, agricultural/grasslands, and wetlands) to store carbon, with forests having the greatest propensity. In terms of bioenergy crops, she explained that they can provide carbon storage, particularly at depth, and that they also have the potential to restore degraded soils, especially from intensive agricultural systems. Professor Berhe presented data that showed 120 petagrams of carbon has been lost from degraded soils from the top 2 meters of soil, mostly in the last 200 years. She explained that we need to ensure that bioenergy systems have safeguards in place so that soil health is prioritized and food security is not compromised.

Professor Berhe's presentation was followed by a Q&A session. She was asked about how various feedstocks compare in terms of their ability to store carbon, and she replied that grasses are very good at storing carbon and that deep-rooting grasses not only provide deep soil carbon storage, but also long-term storage. She was also asked about how the rates of carbon sequestration may change over time. Professor Berhe responded that degraded soils accumulate carbon quickly at first but then slow down to reach a plateau when arriving at steady-state conditions. Dr. Berhe was also asked about the intersection of energy justice with bioenergy crops. She responded that we must think carefully about where to place bioenergy systems, as they could potentially displace food crops and make food either more costly or less secure, particularly for people that did not cause the climate crisis in the first place and have the least flexibility in purchasing more costly food.

Highlights from Previous Federal Programs on Soil Carbon and Current Agency Perspectives/Directions

Representatives from DOE's Advanced Research Projects Agency–Energy (ARPA-E), DOE's Office of Science, USDA's National Institute of Food and Agriculture, USDA's Forest Service, USDA's Agricultural Research Service (ARS), USDA's Natural Resources Conservation Service, and the National Science Foundation (NSF) spoke about their organization's role in soil carbon and bioenergy. Current research topics included climate-smart agricultural practices, biochar, advanced crop breeding, the microbiome, and the collection and analysis of soil data. Anticipated future work included introduction of new crops and soil amendments, integrating agricultural systems and carbon removal, pilot programs for low-carbon forestry and farm operations, and new tools for analysis of soil carbon data.

Engineering and Managing Terrestrial Ecosystems for Optimized Carbon Dioxide Removal and Negative-Emissions Pathways

Dr. David Babson, DOE, Advanced Research Projects Agency–Energy, outlined climate-relevant work at ARPA-E to overcome high-risk technological barriers for abating, mitigating, and removing greenhouse gas emissions. He highlighted technologies in the agricultural sector that can be low cost, low energy, and large scale. Among the practically achievable technologies, he identified cover crops, no-till agriculture, precision animal manure application, and rotational grazing. In the frontier technology sector, he referenced biochar, advanced crop breeding, and crop phenotyping/genotyping for high-carbon-input root systems. Current investments by ARPA-E include the Transportation Energy Resources from Renewable Agriculture (TERRA), Rhizosphere Observation Optimizing Terrestrial Sequestration (ROOTS), and Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management (SMARTFARM) programs, which center on feedstock production for biofuels. The TERRA-ROOTS programs use advanced phenotyping, high-throughput field data collection, and data analytics to improve crop genetics for yield, resilience, nutrient acquisition, and carbon storage. SMARTFARM was founded to interconnect climate-smart farm practices with carbon markets. The program improves the ability of low-carbon fuel standards to decarbonize feedstock production through reliable, accurate, and cost-effective feedstock carbon intensity measurements. Energy and Carbon Optimized Synthesis for the Bioeconomy (ECOSynBio) is another program that aims to use synthetic biology tools to engineer novel biomass conversion platforms and systems. Future work will learn from these projects to create integrated systems with new crops, soil amendments, management, and market strategies that enable net-negative-carbon farming.

Microbiome Research for Carbon Cycling and Sustainable Bioenergy Feedstocks in Biological and Environmental Research's Genomic Science Program

Dr. Boris Wawrik, DOE, Office of Science, Biological and Environmental Research, presented on work in Biological Systems Science Division in Bioenergy Research, Biosystems Design, and Microbiome Science, as well as underpinning work. Among these, he highlighted the Genomic Science Program, which works on enhancing biomass productivity through crop rigor, resource use efficiency, and resilience to abiotic stress. Additionally, this program works on the role of the microbiome in biomass productivity, performance, and sustainability. Examples included experiments from the Fabricated Ecosystems (EcoFAB) program, which grow plants in artificial soils with artificial microbial communities in highly reproducible ways, and rhizosphere-on-a-chip, which examines root exudates and rhizosphere formation. He also highlighted the Biosystems Design portfolio, which engineers new innovative systems with genome-scale engineering, high-throughput screening and testing, new platform organisms, and customized microbial consortia. Finally, he described environmental microbiome research, which studies biogeochemical processes and mechanistic microbial activities for long-term predictive understanding. Other roles of the Biological and Environmental Research program included support for the Joint Genome Institute, bioimaging and characterization, and computational biology.

USDA Soil Carbon Research and Management

Dr. Sandeep Kumar of the National Institute of Food and Agriculture discussed the Agriculture and Food Research Initiative (AFRI), which supports soil carbon initiatives through various grants and partnerships. These include Soil Health (A1401), which advances scientific understanding of soil carbon processes and interactions, large grants for sustainable agriculture systems, and crosscutting topics in agricultural microbiomes, research and extension, and climate hub partnerships. He also highlighted some non-AFRI programs including Small Business Innovation Research (SBIR) funding for natural resource conservation, organic agriculture, and farm of the future.

Dr. Peter Vadas introduced the ARS National Research Programs, including Crop Production, Plant Genetic Resources, Soil and Air, Sustainable Agricultural Research Systems Research, and the Grass, Forage, and Rangeland Agroecosystems.

Dr. Anne Marsh at the Forest Service discussed the Forest Service's role in inventory and trend analysis, as well as applied science for forest and rangelands. She emphasized resources such as their experimental forests and ranges, long-term soil productivity network, and R&D into biogeochemistry, global change, and biochar. She discussed soil carbon in the forest system's planning and management strategies, including mine land reclamation, collaborative forestry landscape restoration, and burned area response. She presented on state and private forestry resources such as the National Agroforestry Center and Community Forestry. Finally, she referenced the USDA Climate Hubs as resources for data synthesis on climate and soil carbon.

Dr. Michael Robotham, USDA, presented on the Natural Resources Conservation Service and Farm Production and Conservation activities related to soil carbon. This included data collection efforts, modeling efforts (including COMET-Farm and COMET-Planner), and collaborative efforts. He also discussed the recent partnership for climate-smart commodities, which allocated $1 billion to pilot projects with agricultural and forestry producers.

All speakers emphasized the importance of soil health for USDA's mission in sustainable crop production and maintenance of healthy ecosystems.

The Recent Evolution of Sustainability Research at NSF in Relation to Soil Science and Engineering

Dr. Brandi Schottel, National Science Foundation, laid out the broad range of funding at NSF for soil science and sustainability. She described NSF's question-driven Long-Term Ecological Research sites where data on organic matter, nutrient cycles, and soil disturbance are collected and collated. The Kellogg Biological Station was especially noted for its work on topics related to the bioeconomy and agriculture. She next discussed resources through the National Ecological Observatory Network, which has unique regional coordination of field and lab infrastructure, including soil instrumentation and terrestrial observation. Finally, she discussed the now defunct Innovations at the Nexus of Food, Energy, and Water Systems program, which produced the Signals in the Soil program. These awards updated soil models and developed new sensors.

Mechanisms of Soil Carbon Storage

Over the past 10 years, soil scientists have made enormous breakthroughs in understanding and explaining the mechanisms of soil carbon storage across environmental systems. Speakers provided summaries of edaphic factors affecting storage rates and capacity, particularly highlighting recent work differentiating across soil textures and mineralogy. Speakers provided an important foundation for understanding the potential of soil carbon storage and explaining the uncertainty and variability often observed in storage estimates.

Factors Affecting Organic Carbon Stability/Sequestration in Agricultural Soils

Professor Keith Paustian, Colorado State University, presented on factors controlling soil carbon sequestration, including climate, soil properties (such as texture, mineralogy, and depth), topography, and previous use. He noted that carbon has been lost from soils due to human-caused land use from grazing land and cropland. Future land management, though, can be used for soil carbon sequestration when purposed for building soil carbon stock. Conventional land management practices that can be more widely adopted include diversified crop rotations, cover crops, no-till, improved grazing systems, restoration of grassland and peat soils, agroforestry, and use of compost. In addition to conventional practices, Professor Paustian spoke of frontier technologies, which are either in an early stage of development or have significant technical or economic constraints to widespread adoption. These technologies include biochar amendments, annual crops with enhanced roots, perennial grains, and deep burial of organic matter. Professor Paustian stated that quantifying soil carbon stocks and greenhouse gas emissions is difficult because (1) emissions and sinks are dispersed, non-point sources—often spatially and temporally variable; (2) there is a low signal-to-noise ratio for documenting annual changes; and (3) rates of carbon stock change are controlled by many interacting processes. Improving accuracy and reducing costs are key to increasing investment in soil carbon as a decarbonization approach. Finally, Professor Paustian concluded with three priorities: (1) a national soil monitoring system, (2) more tightly integrated modeling and observational platforms utilizing big data approaches (e.g., high-resolution remote sensing, ground sensors, and management data), and (3) next-generation field performance "test bed" facilities for evaluating "frontier technologies."

The Efficacy of Amelioration Practices for Crop Residue Removal in the Western Corn Belt

Dr. Virginia Jin, USDA-ARS, discussed the effect of amelioration practices for crop residue removal in relation to soil carbon levels. Wind and water erosion can physically remove carbon and other nutrients from soil, whereas no-till practices and adding a cover crop or manure are likely to get carbon back into the soil. Dr. Jin then identified USDA's research questions and approach related to this topic, including identifying the impacts of corn stover removal on crops and soils and how these impacts differ between intensive versus marginally productive systems. She identified the USDA-ARS REAP project that was a multi-site study across the United States examining effects of location, climate, and soil type on soil health. When comparing annual versus perennial feedstocks on marginal lands, Dr. Jin showed that while no-till corn can be considered GHG-neutral, continuous switchgrass and rotational switchgrass can be considered GHG-neutral or a GHG sink due to the greater storage of soil organic carbon (SOC). Dr. Jin stated that in her experience, a farmer would need to produce at least 180 bushels/acre for adequate organic matter return and soil cover and target removing no more than 2 tons/acre in alternating years.

Biochar Impact on Soil Carbon Sequestration and Sustainability of Crop Residue Harvesting for Bioenergy

Professor David Laird, Iowa State University, first presented on the deleterious impact of residue removal on soil organic carbon. Professor Laird then discussed how biochar can be used to sequester carbon in soils, with a half-life of over 100 years, reflecting its recalcitrancy in soils. Other benefits of biochar are that it reduces soil bulk density; increases soil porosity, soil water retention, and nutrient cycling; recycles nutrients; and enhances overall soil quality/health. However, significant knowledge gaps were identified, such as the value proposition for the farmer (e.g., higher yields are not universal for all soils and climates, ecosystem services may be discounted); identifying the optimum management strategy for different soils, climates, and crops; and defining biochar quality due to the diversity of biomass sources used to make biochar. From various lab and field study results, Professor Laird showed that biochar addition in certain cases increased soil carbon levels and effectively increased the carbon sink capacity of the soil, which allows more residues to be collected without reducing SOC levels. He ended with a vision of a distributed network of local pyrolyzers producing biochar, biofuels, and products with a carbon trading/credits program to make this process economical.

Management Strategies to Optimize Soil Carbon Storage

In this series, speakers shared background information on how climate-smart agricultural management strategies might be applied to bioenergy systems. Key points included concerns regarding leakage and the need for robust management and verification methods. Meta-analysis and modeling were presented as important tools in this effort. Multiple speakers pointed to possible maximum storage capacity of soils for soil carbon.

Systems Perspectives on Carbon Storage by Bioenergy Crops

Professor Tom Richard, Penn State University, presented a series of projections detailing potential pathways to achieving net-negative emissions by 2050. Reaching the necessary carbon reductions would likely result in the creation of a trillion-plus-dollar industry focused on carbon reduction and utilization. Projections included an emphasis on the abundant amount of carbon sequestered through photosynthesis, noting that the planet has net-negative emissions during the summer and spring, but that reverses during the winter months (specific to the northern hemisphere). On a global scale, the acceleration of photosynthesis is more than sufficient for typical carbon emissions. Leveraging natural solutions has many benefits (e.g., low cost, large volumes, rural economic development, and synergies surrounding biodiversity, water quality, and soil health), but multiple challenges arise, including (1) additionality, meaning achieving credits for additional carbon sequestered that would not have happened without outside intervention; (2) leakage from indirect land use change (LUC), which is something that has been reduced but not to a level that is negligible; (3) reversals from direct LUC need various mechanisms (e.g., policies and procedures) to ensure it does not occur—these mechanisms will prevent carbon from being released via soil that was designated for sequestration; (4) permanence is not guaranteed—soil kinetics will increase as temperature changes occur in the future, and this is something that needs to be anticipated in projections; and (5) uncertainty and verification are being addressed through satellite imagery work and increasingly sophisticated agro-ecosystem models. An interface aimed at improving verification, Carbon4Good, aims to educate smaller farm owners on the needs for offsetting and blockchain accounting.

Quantifying Climate-Smart Agriculture Management Impacts on Soil Carbon Storage and Greenhouse Gas Emissions at Multiple Scales

Professor Wei Ren, University of Kentucky, presented on climate-smart agriculture and its impacts on soil health, food security, and climate resilience. Some climate-smart agriculture practices include but are not limited to reduced/no-till, cover crops, biochar, diverse varieties/breeds, and improved nitrogen fertilizer use. Measuring and quantifying climate-smart agriculture at multiple scales requires different data points and types of analysis. This need provides opportunities for the development of field experiments, sensors, remote sensing, numerical models, and meta-analysis and other data analytics tools. Dr. Ren presented on a meta-analysis review that was conducted to see climate-smart agriculture's impacts on soil carbon storage and considered regulations and environmental factors. Projections show that cover crops greatly benefit the rate of soil carbon sequestration. Overall, climate-smart agriculture provides opportunities to make bioenergy crops much more environmentally friendly.

Carbon Farming: How Plant Roots, Microbial Ecophysiology, and Soil Minerals Shape the Fate and Persistence of Carbon in Bioenergy Systems

Dr. Jennifer Pett-Ridge, Lawrence Livermore National Laboratory, presented on broad, national analyses of soil carbon solutions. She highlighted cover crops and deep-rooted perennials for their lower risk, higher measurability, and greater additionality than many other soil solutions. She presented data on these deep-rooted perennials, showing evidence that they could double soil carbon over a decade of growth, and discussed mechanisms for these differences. She also found that marginal, more highly weathered soils had more potential to sequester additional deep carbon. Analysis of biogeochemistry has also found that different ecosystem types accrue carbon in different fractions, which affects the durability and persistence of storage. The impact of the microbiome was also highlighted, particularly that of arbuscular mycorrhizae. These symbionts were highlighted for their ability to alleviate water stress, provide plant nutrients, and transport plant fixed carbon to soil mineral fractions. Overall, Dr. Pett-Ridge highlighted key research opportunities including engineering deeper plant-rooting systems, adding mineralogy into SOC models, enhancing plant exudation (extracellular polysaccharides), and increasing the role of symbiotic mycorrhizae in commercial systems.

Forest Management Practices to Optimize Soil Carbon Storage

Speakers covered a wide range of topics, from the role of woody energy crops in carbon storage to forest management for overall decarbonization. Short-rotation coppiced willow was shown to increase soil carbon in deep soils, but longer-term studies may be required to reduce uncertainty. Biochar was suggested as an opportunity to return carbon to managed forest systems. LUC, in some instances, was highlighted as a concern, which might lead to net loss of carbon from an ecosystem.

Importance of Soil Carbon and Below-Ground Biomass on Greenhouse Gas Balance in Willow Biomass Crops

Professor Tim Volk, State University of New York College of Environmental Science and Forestry, described how biomass willow has been developed as a woody feedstock resource over the past several decades. After planting, the willows are harvested every 3 years for up to seven crop cycles. In upstate New York, cropland converted to biomass willow product saw an increase in carbon for some soils (those 30 cm or 100 cm deep). However, conversion of grasslands to biomass willow decreased soil carbon, indicating that this type of LUC is not favorable for sequestration. A large part of the soil carbon on biomass willow fields is in the form of belowground biomass. The amount of belowground biomass differs by both location and cultivar. These differences are enough to have a significant impact on life cycle analysis and GHG emissions. Since belowground biomass and soil carbon have only been studied for 10 years, there is a lack of understanding of the long-term impacts of biomass willow production on soil carbon storage. Key takeaway points from this early research effort are: (1) changes in soil carbon and belowground biomass have a large impact on the overall GHG balance of biomass willow cropping systems; (2) soil carbon and belowground biomass data are limited, often associated with short-term studies, and do not include the spatial variation in large-scale plantings; and (3) to accurately assess GHG balance of biomass willow systems, there is a need for long-term data for soil carbon and belowground biomass across a range of sites and cultivars. Questions remain about soil and belowground carbon at the end-of-life cycle of the biomass willow crop if it is removed.

Sustainable Forest Management for Increasing Soil Carbon Sequestration with Biochar

Dr. Carlos Rodriguez Franco, U.S. Forest Service, discussed the land area of the world that is covered in forests, woodlands, and mangroves. Tree cover is the predominant land cover on earth. Forest and other vegetated land areas provide a large net carbon sink. The ability of vegetative land to store carbon is greatly affected by natural and human-made disturbances and the growing conditions for plants/trees. The U.S. Forest Service is assessing how major disturbances and climate change are affecting forest inventory and growth and how this affects sustainability. Forest management and silviculture are the best approaches to bring forests stressed from disturbance and climate stress back to healthy resilient forests. These active approaches are a way to increase spatial heterogeneity in terms of composition, age, structure, and spatial distribution in natural forest, which is important for creating biodiversity. Active forest management is a way to increase carbon sequestration and a place where biochar can make an impact. Benefits of producing biochar from forest management activities are: (1) increasing resilience for better adaptation to climate change, increasing forest productivity, decreasing insect and disease attacks, and increasing other environmental benefits such as water retention; (2) high-carbon biochar, when used as a soil amendment on poor mineral soils, is a perfect tool for carbon sequestration, and (3) when net carbon balance in the forest ecosystem is positive, biochar can actively remove atmospheric CO_2. The restoration activities that will produce the residues used in the biochar production, and the biochar production itself, will create sustainable, healthy forests and economic opportunities in rural areas; reduce the risk of catastrophic fires; and contribute to decreased impacts of climate change.

A Circular Forest and Biomass Energy Decarbonization System for Bioeconomy

Professor Jingxin Wang, West Virginia University, discussed circular systems for decarbonizing forest supply chains. His modeling research examined practices such as forestation, sustainable management, land reclamation, bioenergy with carbon capture and storage (BECCS), and biochar production and application on forested lands, and then assessed carbon sequestration rates, costs, and CO_2 utilization costs (as adjusted for revenues, byproducts, credits, and fees) as found in the literature. He found particularly high rates of sequestration in land reclamation by using shrub willow over multiple decades. BECCS, forestation, sustainable management, and biochar were reported to have sequestration rates 1–2 orders of magnitude slower. Sequestration costs had wide margins of error in forestation and management and biochar. Similarly, CO_2 utilization ranged widely. Forestation and management solutions ranged from negative to very expensive. These estimates were used to estimate ideal forest harvest rates, management, and end use strategies. Conversion of wood to pellets was found to have the lowest global warming potential, as well as consuming the least water and fossil fuel. Pyrolysis to oil production emitted the most, with the largest emissions generated by the conversion process.

Agricultural Management Practices to Optimize Soil Carbon Storage

This session demonstrated the importance of long-term data sets, management, and edaphic factors in soil carbon storage in bioenergy systems. Speakers identified that in long-term experiments, there was typically no net carbon accrual but that there was significant variability across sites and soil fractions. Particulate- versus mineral-associated organic matter impacted soil carbon outcomes and accumulation, as well as the accrual of biochar. Systems discussed included switchgrass, corn, and sorghum.

Not All Soil Carbon Is Made Equal: How Biofuel Crops May Increase Particulate or Mineral Associated Organic Matter

Professor Francesca Cotrufo, *Colorado State University*, shared that it is essential to understand soil carbon properties such as particulate organic matter (POM) versus mineral-associated organic matter (MAOM) to accurately assess vulnerability, persistence, potential for storage, nitrogen demands, saturation levels, and management strategies, and to create accurate integrated measurements and models for carbon markets. She highlighted how input of roots versus shoots, or root exudates, resulted in both different carbon sequestration rates and organic matter types. For example, in sorghum, root structural inputs resulted in more POM, while the more labile shoots resulted in more MAOM. She also showed how reducing the C:N ratio, as with legume cover crops, can increase MAOM accrual and persistence. A recent study she presented showed that particulate organic carbon was found to be more responsive to regenerative practices than MAOM or SOC as a whole. Professor Cotrufo concluded with four guideposts for soil carbon storage: (1) increase structural inputs belowground with larger and deeper crop roots, (2) increase soluble, low-C/N inputs to increase MAOM, (3) reduce disturbance via no-till, and (4) use perennial cover to increase both POM and MAOM. POM will be more responsive than MAOM to all treatments, being more directly linked to plant inputs and being most vulnerable to disturbance. A follow-up question was how MAOM and POM fractions interacted with biochar. Professor Cotrufo responded that while in the short term biochar was most likely to associate with the light POM fraction, their decadelong experiments found pyrogenic carbon across the soil organic matter fractions.

Potential for Carbon Accrual in Bioenergy Feedstock Fields

Dr. Kirsten Hofmockel, Pacific Northwest National Laboratory, reflected on the massive loss of carbon from soils that has already occurred due to agriculture. In this context, it is important to understand the drivers of persistent carbon storage through microbial controls, cropping systems, and soil habitat. Long-term research sites for bioenergy crops and soils (such as Kellogg Biological Station and the Arlington Agricultural Research Station) are essential to this research. Their research identified target fungi and other microbes for managing biotic impacts on soil organic carbon. Additionally, they identified key edaphic traits, such as soil fraction and texture, that regulated sink capacity. They found the highest accumulation of carbon in the light mineral-associated organic matter fraction, potentially due to enrichment with amorphous iron-bearing minerals. Finally, they found that there was a need to consider the mass balance of the entire system, including hydrologic transport to deeper soil horizons. Dr. Hofmockel concluded by sharing data from long-term research sites, where they generally found that bioenergy field management resulted in no change in soil carbon after 8 years, but she stated that exploring accumulation in specific fractions could better elucidate factors driving soil carbon sequestration.

Soil Carbon Sequestration by Switchgrass: Potential and Management

Dr. Mark Liebig, USDA-ARS, discussed attributes of switchgrass, which has a large percentage of root biomass (>75% of total biomass) and roots that can extend below 2 meters. His work focused on the potential role switchgrass has in soil carbon storage and the specifics of management and site controls. He presented research focused on the northern Great Plains/western Corn Belt, which is an area with an abundance of saline-affected soils and recent shifts in crop portfolios due to climate change. He examined research from 2000–2011 across South Dakota, North Dakota, and Nebraska. Across 10 sites, carbon accrual was minimal, but SOC increases were statistically significant for 4 of 10 sites. If accrual occurred, it tended to occur at the surface and below 30 cm and to be very site specific. Increasing fertility seemed to increase soil organic carbon accrual, while harvesting time had no impact. Overall, he found that marginal soils may accrue little to no soil carbon under switchgrass. He identified drought effects on soil carbon dynamics and subsequent biomass production as an important area of future research, particularly as the climate changes.

Research and Development Needed to Support Policy for Soil Carbon Storage in Bioenergy

This session focused on needed investments in research and development to support policies to promote soil carbon storage in bioenergy. Biochar research was emphasized, as well as tools for quantifying soil carbon. One of the speakers cautioned against overemphasizing the role that soil carbon storage can play in mitigating climate change and to focus on holistic practices that promote soil health.

Biochar at the Interface of Energy Transition and Regenerative Agriculture

Dr. Ghasideh Pourhashem, Genomatica, and Dr. Elsie Hung, Rice University, discussed support for biochar as a soil conservation practice, such as commercial financial incentives, policy support, and research and development funding. Their analysis identified various implicit and explicit commercial and government agency support for biochar. Analyzing these existing programs, they suggested that there was an insufficient focus on incentives for biorefinery coproducts with environmental benefit, soil security, and soil carbon storage. They also found that many programs are designed for already commercial-scale productions. They identified proposed pieces of legislation that could relate to biochar. Among the proposed legislation, they identified that there was increasing attention to biochar as a soil amendment and carbon sequestration tool. They identified barriers to policy support for biochar as (1) setting metrics given the high variability in biochar performance; (2) limited data on biochar performance, benefits, and production cost; and (3) limited mechanisms that allow control and reduction of point-source pollution. Their recommendations for future policy included (1) take advantage of biorefinery coproduct programs, (2) consider soil security a national priority, (3) conduct research to monetize the ecological benefit of biochar applications, (4) target programs for biorefinery products toward those with multiple environmental products, (5) make improvements to carbon accounting modeling to track carbon across mediums and temporal boundaries, and (6) higher payments by carbon emitters.

Research Priorities in Soil Health and Carbon Storage for Production of Bioenergy Crops

Dr. Cristine Morgan, Soil Health Institute, discussed principles for soil carbon storage applicable to bioenergy systems. In bioenergy, biomass removal and soil compaction act to reduce soil carbon storage. However, cover cropping and perennial crops in biofuel systems minimize disturbance, keep soil covered, and promote high photosynthesis. She identified major scientific research needs associated with bioenergy, such as optimizing nutrient cycling and nitrogen supply and increasing photosynthetic allocations to the soil. She also discussed the research in support of policy that is needed, particularly measuring soil carbon at scale. Here, she highlighted the need to retrain commercial labs from testing for soil fertility to soil carbon, as well as expanding tools for proximal sensing with remote sensing, measuring bulk density, and measuring carbon stored at depth.

Realizing Soil Carbon Sequestration: Research Gaps in the Context of Biofuels

Professor Ronald Amundson, University of California, Berkeley, discussed the difference between technical and achievable potential for soil carbon storage. He identified the complexities of restoring carbon to soils in the context of interactions between nutrient inputs, erosion, and soil production. He expressed skepticism of goals to reach carbon-neutral agriculture within the next few decades, given current emissions rates and high erosion rates from agriculture. He framed U.S. agriculture as soil nutrient mining with a need for circular practices to restore lost zinc, copper, and silicon. Professor Amundson also cited a recent paper that suggested that the maximum sequestration rate of global cropland might be lower than prior estimates. Finally, he concluded by recommending caution on overemphasizing the capacity of soil carbon storage, the need to consider costs of carbon storage in soils, and finally the value of holistic approaches to soil health that examine broader sustainability.

Tools for Decision Making in Bioenergy and Soil Carbon Storage

Speakers highlighted systems, frameworks, and models that are enabling better measurement and verification of soil carbon storage by bioenergy systems. These included the SYMFONI project, which holistically tracks carbon budgets across farm fields, updates to CENTURY-based models with county-level carbon budget capabilities, and advances in process-based models to move beyond DAYCENT-derived parameters toward new paradigms such as MEMS and Cycle.

SYMFONI - A "System-of-Systems" Solution to Quantify Carbon Outcome for Bioenergy Feedstock Production at the Field Level

Professor Kaiyu Guan, University of Illinois at Urbana-Champaign, presented his SYMFONI project, which is funded by DOE ARPA-E's SMARTFARM program. The SYMFONI modeling framework represents a "system-of-systems" solution that integrates field accuracy, scalability, and cost considerations into quantifying field-level carbon credits for bioenergy feedstock production. This framework tracks holistic carbon budgets for individual fields, from aboveground to belowground, for every field in the Midwestern United States and beyond. Every farmland is unique, and quantification of carbon credits at the field level is critical. Such quantification needs to consider three dimensions: crop characteristics (e.g., crop type, variety traits, phenology, water use, response to stress), management practices (e.g., planting/harvesting, tillage, cover cropping, intercropping, crop rotation, fertilizer/pesticide application), and environmental parameters (e.g., weather, soil condition). Professor Guan takes a hybrid approach that utilizes machine learning and radiative transfer models to quantify crop nitrogen across scales. Satellite fusion technology is developed by using scalable fusion algorithms combined with various public satellite data to generate high-resolution, daily, and cloud-/gap-free images and data sets at the field level from 2000 to present. These data are very useful to understand crop photosynthesis, farmland carbon uptake, and the impact of agriculture practices at the field scale. He discussed the challenges of model development and noted that quantifying the carbon income is complex and requires process-level understanding. His work has attracted great attention for technology transfer and commercialization.

Soil Organic Carbon Modeling to Support a Feedstock-Level Biofuel Life Cycle Analysis

Dr. Hoyoung Kwon, Argonne National Laboratory, discussed their soil carbon modeling efforts supported by DOE-BETO and the ARPA-E SMARTFARM program. Argonne has incorporated SOC changes from LUC for large-scale biofuel feedstock production into biofuel life cycle analysis (LCA). The impacts of land management changes on feedstock CI have received a lot of attention. Research has identified that feedstock production contributes to 40% of overall corn ethanol GHG emissions. Feedstock CI from farm energy and material use can vary significantly across different Midwest states, and this reflects variations in soil fertility, climate, and farming practices. Further analysis shows that SOC changes from adopting various farming practices can significantly affect the CI of feedstock production. Both SOC change and energy/material inputs affect the cradle-to-farm-gate GHG emissions. Shifting current farming practices to no-till, cover crops, and manure application can produce low-CI feedstocks for biofuel production. Sophisticated modeling frameworks have provided reliable and cost-effective estimates of SOC changes. Among many models, CENTURY-derived models are being used by the U.S. Environmental Protection Agency and USDA for national GHG inventory development and to inform policy. Argonne has developed a parameterized version of CENTURY to generate U.S. county-level SOC changes. Their work simulates the long-term dynamics of SOC changes from 1880 to 2020 to understand the impacts of LUC and to develop projections. Dr. Kwon commented that modeling SOC changes continues to be improved and evolved. It is important to promote the certification of low-carbon feedstock production practices by linking data, model, and in situ sensing.

Assessing the Role of Soils in Carbon-Negative Bioenergy Landscapes

John Field, Oak Ridge National Laboratory, started his presentation by highlighting some previous biofuels LCA studies on assessing various biofuel feedstocks production, associated SOC changes, and impacts on carbon footprint. He discussed scenarios of SOC as either liability or opportunity. His 2020 publication in the *Proceedings of the National Academy of Sciences* reported the carbon fluxes for a future biofuel BECCS scenario on abandoned cropland and found that soil carbon sequestration improves the overall footprint of biofuels production, but it is a relatively small term compared to fossil fuel displacement. SOC punches above its CO_2-equivalent weight in terms of soil health co-benefits, increased emphasis on carbon removal and carbon management, and public perceptions of natural climate solutions. Therefore, it is important to optimize the soil carbon sequestration for bioenergy systems via carbon management, landscape design, and crop belowground traits. His work uses process-based ecosystem models (such as DayCent), and he integrates parameters including land quality, management intensity, yields, SOC response, and nitrous oxide emissions into the model. He presented three Oak Ridge National Laboratory studies on SOC optimization. The first study demonstrated that climate-smart agriculture practices, such as no-till or poultry litter, are effective in carinata crop management to achieve net SOC benefit for sustainable aviation fuel production. The second study took a landscape design approach to cultivate switchgrass for a commercial biorefinery and was able to improve carbon storage capacity for full life cycle benefits. He shared the third study, which is currently being performed at the Center for Bioenergy Innovation, on optimizing crop belowground traits without sacrificing aboveground biomass quantity or quality. He commented that there are a lot of opportunities in moving beyond the legacy models such as DayCent and integrating new data such as different forms of SOC, saturation effects, and deep soil carbon. He acknowledged the value in new paradigm models such as MEMS (Colorado State University) and Cycle (Penn State University).

3 × 5 Speakers, Summary of Contributed Lightning Talks

BETO provided an opportunity for stakeholders to submit presentations for a "3 × 5" lightning talk session, in which presenters were given up to 5 minutes and three slides (in addition to a title slide).

Investigating Soil Carbon Vulnerability and Bioenergy Sustainability under Changing Climate

Umakant Mishra, Sandia National Laboratories, summarized Sandia's large body of work that uses machine learning and other models to predict the vulnerability of continental U.S. surface soil organic carbon stocks under a variety of scenarios. Dr. Mishra showed modeling results of the predicted impacts of switchgrass and sorghum cultivation on changes in SOC and carbon emissions, respectively. The results showed large regional variability across the United States, highlighting the importance of both soil- and site-specific considerations in bioenergy crop cultivation decisions and national-scale modeling in predicting the full potential of energy crops for soil carbon storage.

Understanding Soil Systems: Measuring & Driving Carbon Underground

Ben Brown, Arva Intelligence, described the data analytics tool produced by Arva Intelligence that takes numerous data inputs (e.g., environmental, remote sensing, operational) tied to agricultural practices and creates a decision-making platform to help farmers optimize agronomic practices in conjunction with maximizing profit, soil health, and environmental benefits. Dr. Brown made the point that carbon could actually be considered the first "crop" that farmers can farm, and it does not have to be transported. Dr. Brown emphasized the importance of high-resolution data and showed within-field variability in total organic matter ranging from 0.5% to 3.5%.

Washington Soil Health Initiative

Chris Benedict, Washington State University, talked about the Washington Soil Health Initiative, a coordinated statewide soil health effort across three agencies within Washington state. The initiative published a roadmap in 2021, which led to a paradigm shift in state investment in soil research outreach and incentive programs. They also initiated a process to create a densely concentrated network of long-term agroecological research sites funded in perpetuity and created a program that will incentivize landowners to undertake soil health practices.

Soil-Water-Plant Nexus: Controlling the Fate of Carbon Sequestration through Microbiome Engineering

Marie Kroeger, Los Alamos National Laboratory Bioproduct, brought attention to how to potentially control the fate of carbon sequestration at the soil-water-plant nexus through the microbiome. Dr. Kroeger raised the point that, in addition to working to directly increase carbon in the soil, very important aspects of building healthy soils are to decrease soil erosion and, especially in the case of bioenergy crops, grow crops with low water and nutrient inputs. Dr. Kroeger showed recent findings from the literature that soil erosion and water stress are increasing, exacerbated by climate change. She went on to describe how soil water repellency is a global phenomenon that is a major cause of soil erosion and inefficient water use and how it is driven by the soil microbiome. Dr. Kroeger received questions about the soil microbiome in fire-damaged soils and replied that post-fire, there can be increased soil water hydrophobicity, which leads to flooding and mudslides.

Bioproduct Agroecosystems as a Sustainable Post-Mining Land Use in Appalachia, USA

Zac Freedman, University of Wisconsin-Madison, described his team's work dedicated to finding the best ways to rejuvenate lands scarred by surface mining, which has affected greater than 2.5 million acres of land in the United States alone. Professor Freedman and his team looked at maps of biomass potential and planted *Miscanthus* on a former surface-mined site in West Virginia. The *Miscanthus* biomass can be used to make various bioproducts. They attempted to directly and indirectly manipulate the soil microbiome using soil amendments and by adding a transplanted microbiome from a high-yielding *Miscanthus* stand on a formerly surface-mined site, with the goal of increasing crop yield and building stable soil carbon. After 3 years of growth, they found the *Miscanthus* had comparable yields to *Miscanthus* grown on other marginal soils, and they found treatments that resulted in increased soil organic matter content and increased microbial carbon use efficiency. In response to a question from the audience on whether the quality of the biomass is affected in terms of potentially higher levels of heavy metals or other mining materials, Professor Freedman replied that they are very interested in answering that question and have plans to analyze the plant tissue in coming years.

Returning to Traditions: Native American Land Stewardship Techniques Provide Solutions to Growing Global Climate-Change Issues

Mary Belle Zook, Indigenous Food and Agriculture Initiative at the University of Arkansas School of Law and Citizen of the Potawatomi Nation, described how Native Americans hold valuable knowledge and a keen understanding of ways to sustainably manage land resources, and this understanding is proving especially valuable as climate change and population growth continue to have increasingly negative impacts. For example, cover crops and regenerative agriculture techniques date back to Indigenous peoples' traditional ways, and native plants have root systems that reach deep and loosen the soil and increase water retention. With more one-day precipitation events and longer dry periods in between, if the soil cannot absorb enough water, this has negative impacts on everything from crop production to wildfires and animal production. Additionally, utilizing regenerative agriculture techniques can help reverse topsoil degradation caused by conventional agriculture and assist with environmental cleanups, such as the Quapaw Nation's work in Picher, Oklahoma, and other U.S. Environmental Protection Agency Superfund sites across the tribe's jurisdiction.

Other examples of positive impacts of Indigenous peoples' traditional ways include bison reclamation that has assisted with prairie grassland restoration and the plains, wild rice reclamation that has increased biodiversity in the Great Lakes region, and traditional companion planting techniques, like the three sisters (corn, beans, and squash) that have aided in both small- and large-scale soil remediation in fields and gardens coupled with more nutrient-dense crops. Mary Belle Zook emphasized that they are always looking for ways to improve soil health through training, resources, and partnerships, and when asked for advice on best practices for seeking collaborations with tribal governments, she replied that while every community is different, it is important to build relationships first. This can take time and be difficult, but it is a key part, especially when it comes to any research or capital-based proposals.

Translating Soil Aggregate-Size Understanding of Microbial Carbon Accumulation to Ecosystem-Level Predictions

Jorge Mazza Rodrigues, University of California, Davis, described that to predict long-term soil carbon storage, one must take into account the Venn diagram of interactions among the organic matter chemical structure, the microbiome biological structure, and the soil aggregate physical structure. He showed electron micrographs of soil aggregates isolated from the same soil sample with more than sixfold difference in grams of carbon per gram of soil. To explain this difference, Professor Rodrigues showed associated data that concluded that increased soil carbon is linked to both increased occluded particulate organic matter by forming larger aggregate structures and to increased microbial biomass. Further, Professor Rodrigues' group performed carbon use efficiency measurements on the two soil aggregates using glucose and glutamate and found that carbon use efficiency increased with a higher concentration of organic matter. This was somewhat counterintuitive because one would expect that the microbes that have more carbon would be less efficient at how they utilize the available carbon, but it turns out that it is not only the concentration of carbon but also the chemical structure of the carbon that is available.

Professor Rodrigues' group is now combining these data with metabolomics and supervised machine-learning data using the Millennial model to complete the story.

Mobile Inelastic Neutron Scattering (MINS) Soil Scanning System "In Situ" Soil Analyses

Allen Torbert, USDA ARS, presented a new technology his team has developed for "in situ" soil measurements, called the mobile inelastic neutron scattering (MINS) soil scanning system. The technology has been licensed by a company called Carbon Asset Solutions that is planning to use it worldwide. The system is small enough to be pulled by a tractor or ATV, and after a day of scanning, it produces 3D heat maps of measurements such as carbon, potassium, and moisture. The scanning reaches a depth of 30 cm into the soil, and when paired with in-field bulk density measurements, it can accurately report total carbon by weight. The scanning system is a volumetric measurement of the actual carbon atoms present in the soil being radiated, so factors that normally cause issues for soil carbon analysis (including soil moisture, bulk density, soil type, structure of the carbon compound, and the soil chemical or biological components present) are minimized. Carbon Asset Solutions is developing the mobile units and aiming for a target throughput of being able to scan about 64 acres per hour.

Should I Char It? A Brief Presentation on Biochar for C Management

Thea Whitman, University of Wisconsin-Madison, began her presentation with some definitions. Pyrogenic organic matter is organic matter that has been subjected to incomplete combustion of biomass under low oxygen, and this is the process known as pyrolysis. Biochar is pyrogenic organic matter that is produced intentionally, whether for an agricultural amendment or perhaps in the context of carbon management. Professor Whitman explained that there is potential for biochar systems to produce net carbon drawdown, but there are important considerations. To illustrate this, she showed a schematic of percent carbon remaining in the system over time under different vegetation management scenarios and explained that the initial production of biochar through pyrolysis loses about half of the carbon, but the carbon that remains decays relatively slowly, so the net impact depends on what would have happened to the biomass otherwise. Lastly, Professor Whitman showed analyses of the many factors involved when deciding whether it makes sense to use biomass for bioenergy or biochar. In general, the studies showed that bioenergy is the more carbon-beneficial option, except in scenarios where biochar is alleviating soil fertility constraints and thus leading to increased agricultural yields. The factors to consider include the carbon intensity of the energy that is displaced, the effects of the non-pyrogenic soil organic carbon such as increased mineralization or priming, carbon price, and whether the location is suitable for BECCS. Further pointing to the complexity of the topic, Professor Whitman received one comment pointing to the Innovation for Cool Earth Forum Roadmap that concludes that carbon storage is higher value than the energy use.

Analysis of Key Insights

Stakeholder feedback was organized in terms of key concepts discussed throughout speaker talks and breakout sessions, and the following synthesis was generated:

Management Practices

Biochar Application for Improved Soil Carbon and Agronomic Benefits

Stakeholder interest in biochar was compiled and categorized into the seven areas listed below. A general summary of stakeholder input for each of these interest areas is given:

Biochar Characterization. Stakeholders felt that biochar specifications (e.g., pH, ash/mineral content) for soil application need to be better elucidated. Specifically, data that correlate biochar properties and performance on the field are needed. One example is so-called "designer biochar," which has been converted for specific properties such as higher water retention. Additionally, the correlation between feedstock properties and biochar properties needs to be better understood. The feedstock and process used to produce the biochar will affect the properties of the resulting biochar. The relationship between the method to produce the biochar and the resulting functionality of the biochar needs to be mapped. Biochar characterization also needs established, standardized analytics. Finally, stakeholders were also concerned about potential contaminants in biochar (e.g., undesirable elements/compounds) and how quickly that becomes a problem in soil. For example, seaweed-based biochar may contain high levels of arsenic or salt.

Economics of Biochar. Biochar can be produced as a coproduct alongside biofuels. Stakeholders expressed interest in how biochar can be made economically within a biorefinery for distribution to farmers. Cost is a factor; however, some stakeholders point out that once equipment needs are met, the variable cost of producing biochar comes down, especially if there is a dependable and available source of feedstock and supply/demand increases. However, there is a cost paradox—to stimulate steady demand, price needs to come down and biochar needs to be readily available. For price to come down and a steady supply to be available, production at scale needs to happen, which needs a steady demand. Stakeholders felt that looking for synergies between the processes needed to produce the biochar from biomass and the other processes ongoing at a biofuels plant (e.g., waste heat for ethanol production; syngas can be used to produce electricity) could also help reduce the cost of biochar. Therefore, producing biochar can generate benefits and revenue on several fronts, and coproducts will help to reduce the cost of biochar.

Agronomic Benefits of Biochar. Speakers presented the potential benefits of biochar, including improving soil quality, biomass production, water penetration, and increasing carbon storage. Stakeholders were particularly interested in biochar to improve soil fertility. There was substantial interest in whether biochar generated from conversion of residues could return nutrients to the soil, and to what extent. Participants envisioned solid residues from biomass processing being returned to the soil as biochar, bolstering the circular economy. Stakeholders also cited the potential coproduction with existing bioenergy infrastructure as a reason to investigate biochar.

Application of Biochar. Participants discussed the best methods of applying biochar to soils. Given the wide variability within U.S. soils, there are concerns about how to standardize the application of biochar to all soils. Some recommended co-composting or pretreatment of biochar (such as in a manure lagoon) to make use of the char as a slow-release fertilizer. Others discussed the issue of needing to plow biochar into the soils, which might create trade-offs between biochar use and low-till management. Others suggested the potential to pulse biochar or vermicompost beneath the soil while minimizing disturbance.

Feedstock Choice for Biochar. Participants felt that biochar could be made from almost any organic source. As the most common, they highlighted biochar from woody biomass, such as the slash piles left from forest thinning and other treatments that now constitute a costly disposal problem. They also specified agricultural residues, crops, chicken litter, nut shells, and algae as other common feedstocks. Construction waste wood and waste wood diverted from landfills was another potential feedstock, as was material from tree trimming—residential, municipal, or around power lines. There was specific interest in generating biochar from logging residue for use in mine land reclamation and on Superfund sites.

Environmental Accounting of Biochar. Several participants raised questions about how LCA processes might be applied to biochar production. The primary concern was whether carbon in the biochar was credited at the point when it was produced, at the point it was applied to soils, or whether a more complex interaction (biochar decomposes but enhances the productivity of the overall system) is needed.

Policy Considerations of Biochar. Finally, a number of participants expressed interest in mechanisms for incentivizing and supporting biochar production. These included reclassifying biochar equipment from incinerators to a cleaner burn method, making it easier to include biochar in governmental timber sale/restoration contracts, and lowering the overall cost of biochar by funding projects for coproduction with syngas generation. Participants also expressed interest in a governmental role in the demand side for biochar, suggesting that purchase and use for land restoration would provide confidence in the biochar industry. Barriers to policy support for biochar were setting metrics given the high variability in biochar performance; the limited data on biochar performance, benefits, and production cost; and limited mechanisms that allow control and reduction of point-source pollution. Stakeholders recommended that future policy take advantage of biorefinery coproduct programs, consider soil security a national priority, conduct research to monetize the ecological benefit of biochar applications, target programs for biorefinery products toward those with multiple environmental products, improve carbon accounting modeling to track carbon across mediums and temporal boundaries, and provide higher payments by carbon emitters.

No- or Low-Tillage & Cover Crops

Participants expressed high likelihood in the adoption of low- or no-tillage practices for soil carbon sequestration, as stakeholders have already seen this approach work. No-till and low-till practices were also highly ranked for short-term impact, long-term impact, and persistence, demonstrating that this practice can result in enhanced soil carbon levels over many years. Participants believe cover crops, particularly deep-rooting varieties, are capable of increasing overall soil carbon storage by having more photosynthesis occurring on a given tract of land for a larger portion of the year, even on marginal lands. Participants expressed high likelihood in the adoption of cover crops, with high rankings for short-term and long-term impact. However, cover crops were ranked very low in terms of persistence of soil carbon storage, meaning that once cover crops are no longer grown, the soil carbon benefit could be lost.

Managed Microbiomes

Participants expressed interest in the role of microbiomes, as well as invertebrates and biofilms specifically, in soil carbon sequestration. Participants highlighted several key research needs in this area, including the role of methanotrophs and hydrogenotrophs as biostimulants, managing the microbiome for greater carbon use efficiency, and how agricultural management impacts the role of microbes in soil carbon storage. Current research by DOE Office of Science in this field was highlighted, including the Genomic Sciences Program, the Biosystems Design portfolio, and the Environmental Microbiome Research project. Speakers presented on several relevant research innovations, including the creation of extracellular polysaccharide films by microorganisms for greater soil aggregation and stability, soil moisture retention, nutrient uptake by plants and microbes, and plant-microbe signaling, as well as the role of soil invertebrates in improving soil physical structure by increasing aggregates and soil aeration.

Potential for Soil Carbon Storage

Speakers were invited to discuss the soil carbon storage rate of bioenergy crops and feedstocks. Feedstocks discussed included dedicated energy crops such as switchgrass and willow, agricultural residues such as corn stover, and forest residues. Generally, there was not strong evidence for net carbon accrual in soils by growth of bioenergy crops alone over 0–10-year time scales. Multiple speakers reported that across multiple switchgrass sites, they found little to no accrual of soil carbon. However, at the same time, higher carbon storage was identified at some sites. Therefore, it was suggested that switchgrass had potential to be carbon neutral or a sink depending on circumstance.

Variability from field to field was commented on by many speakers and was generally attributed to the initial soil condition at the site, the depth of soil sampled, and the time horizon of the study. Most commonly cited by speakers was the tendency of marginal and degraded lands to store carbon at higher rates, where speakers found higher rates of storage in soils with already low carbon storage, especially when this was due to past land use. This included recently burned sites or former mining land. Several participants referenced studies showing that such marginal lands had a greater overall capacity for soil carbon storage than healthy soils, which might already be at or near their maximum soil carbon storage capacity. However, there was a great deal of variation from site to site. Speakers found that bioenergy crops have the potential to restore degraded soils, especially from intensive agricultural systems. Some participants argued that restoration of marginal lands presented an opportunity to mitigate concerns about land use and conversion. Making use of marginal lands would avoid displacement of food on croplands by energy crops.

Given adoption of climate-smart agricultural practices, the rate of soil carbon storage via feedstock production greatly increased. Stakeholders generally agreed that adoption of no-till and cover crop rotations resulted in small but significant carbon storage. Use of perennial, deep-rooting grasses, such as switchgrass, generally sequestered more carbon than annual crops. One speaker stated that over 10 years, one could expect twice as much soil carbon in deep-rooted perennials over shallow-rooted annuals when both were grown on marginal lands.

Potential for Retaining Soil Health while Managing for Residue Removal

Removal of waste biomass from agricultural and forest systems can still support a carbon-neutral system in terms of soil carbon storage, depending on the rate of removal. Sustainable residue removal rates, where soil carbon storage was not negatively impacted, ranged widely depending on land use and soil type. The USDA-ARS REAP project, a nationwide study examining effects of location, climate, and soil type on soil health, is working to identify impacts of corn stover removal on crops and soils. Other researchers stated that residue removal may result in loss of soil carbon due to disturbance. Forests were generally believed to be able to support higher residue removal rates without reducing the amount of stored soil carbon.

Participant and speaker comments indicated a wide range of confidence and awareness regarding current science on residue harvest frequency and quantity. Several participants requested additional information regarding the carbon-negative impact of using residues for bioenergy versus leaving them in the field or forest. Participants also expressed interest in understanding how trade-offs were considered in the Billion Ton Report. Participants wanted to better understand how climate, soil type, and crops were considered in estimating trade-offs. Overall, there was a sense from participants that residue removal needed to be treated conservatively, to minimize both direct effects on soil health (compaction, erosion) and indirect effects (reduced fertility, lower carbon storage). Site-specific assessments were deemed important, especially as certain soils, such as those prone to erosion, can only lose a small portion while maintaining soil health.

Some participants discussed forestry specific concerns, such as developing carbon valuation models that help optimize forest harvest scheduling to maximize total revenues in terms of carbon, timber, biofuel feedstock values, and greenhouse gas emissions of the energy product. This is of particular value in forest management due to the time it takes to replace the harvested carbon in the trees, otherwise known as the time it takes to reach carbon neutrality.

Maximum Rate and Storage Potentials for Soil Carbon

A common theme across stakeholder comments was that soil maximum carbon storage may be dictated by climatic and soil conditions, such that storage cannot be meaningfully increased beyond an ecosystem's natural levels. This was frequently referred to as the soil's native condition, with the assumption that soil carbon under native, undisturbed vegetation would have approached the maximum storage capacity for that climate. However, other stakeholders disagreed with the premise that soils might not be able to sequester carbon beyond some initial, pre-degradation point. These stakeholders argued that while it was true that agricultural systems generally retained far less soil carbon than original soils, adoption of advanced conservation techniques had the capacity to restore soils to a steady state of soil carbon greater than the original condition.

While there was not a firm consensus on this issue, there was consensus that degraded lands could be expected to see the greatest overall increase in soil carbon storage, as well as higher rates of accrual, as described above. This was generally attributed to soils accumulating carbon most quickly when well below their native carbon storage condition, before plateauing at a steady-state condition, whether that be the same or above their original state. Speakers provided a range of estimates for the maximum potential of soil carbon storage, depending on which management strategies were assumed. Generally, soil carbon storage represents a small flux.

Durability and Permanence

Stakeholders expressed interest in and concern over the durability and permanence of stored soil carbon. Key points were the vulnerability of sequestered carbon to a cessation or reversal of management, a need to define the minimum time period for sequestration that might be considered acceptable by funders and credit purchasers, and differences in durability across management strategies.

In discussing cessation or reversal of management, participants stated that farmers' needs and motives may change over time, such that many years of carbon accrual might be lost by a single plowing event motivated by socioeconomic factors. While there was not consensus on how to address this issue, many speakers emphasized careful study of farmer needs and motivations, as well as creation of robust agreements for carbon storage with clear time horizons.

Speakers identified a need to identify acceptable time ranges for carbon storage to address uncertain long-term permanence, with time horizons of short term (≤5 years), medium term (6–20 years), and long term (>20 years) suggested. There is a need to decide on a consistent system of measurement between management strategies with different likely time horizons of durability. Considering time horizons can help land managers make decisions while balancing cover crop rotations, which might impact soils over the course of months, and long-lived energy crops such as willow, which might have multidecadal periods of growth between disturbances to root and soil biomass.

Similarly, participants called for standardization of acceptable uncertainty and reliability to better incorporate soil carbon into policy design. Many stakeholders requested information on what uncertainty DOE tolerates in assessing the carbon intensity score of a technology and how these estimates factor into the LCA of bioenergy products. They also raised questions about specific applications, such as what level of certainty is required to create equivalence between soil carbon and other carbon dioxide removal approaches (e.g., geological storage). Multiple participants requested the creation of generally accepted environmental auditing principles that would assess carbon intensity and soil carbon storage.

Measurement, Reporting, and Verification

Soil carbon levels are difficult to measure accurately due to high variability, slow accrual over long time scales, different storage rates by depth and fraction, and inconsistent methodologies for measurement across organizations. Within-field variability of total organic matter can mask whether significant increases in soil carbon levels have occurred, even in fields believed to be homogenous. A summary of stakeholder input that helps to address these issues is given below:

- **Heterogeneity of Soils.** Stakeholders agreed that soils are idiosyncratic and evaluation of carbon sequestration must occur at a farmland level. Three dimensions of farmland were highlighted: crop characteristics (e.g., crop type, variety traits, phenology, water use, response to stress), management practices (e.g., planting/harvesting, tillage, cover cropping, intercropping, crop rotation, fertilizer/pesticide application), and environmental parameters (e.g., weather, soil condition).
- **Measurement of Soil Carbon.** Development of in situ, peripheral, and remote sensing soil measurement techniques was supported. Several technologies can measure instantaneous carbon or be used to detect short-term accrual; however, high variability, cost, and difficulty of implementation can still make it difficult to detect significant change except over long time scales. Stakeholders also suggested integrating new knowledge of specific soil fractions (e.g., labile vs. stable, mineral-associated vs. particulate organic matter, light vs. heavy, organic vs. inorganic) to reduce the number of measurements and increase consistency. Currently, high accuracy is only possible with highly standardized, high-volume field measurements, a task that is laborious, expensive, and hinders landowner recruitment. Improving efficiency, standardization, and availability of soil measurements was generally advocated for by stakeholders.

  Satellite measurements cannot penetrate deep soils and have limited spatial resolution. However, they can be used to determine changes in land use, management, climate, and other soil formation factors. Participants expressed interest in combining new sensor technologies with smart farm technologies already commonly used by farmers to predict metrics such as crop yield. Some participants expressed interest in partnerships to develop this field.
- **Models of Soil Carbon.** Models of soil carbon storage can incorporate sensed data to estimate soil carbon and minimize the number of physical field measurements required. There is a need to understand how well current models can be used to assess soil carbon storage given high variability of soils. There is also a need to identify generalizable ranges for sequestration rates by region and management type, which can be used as stand-ins for site-specific measures. Stakeholders emphasized that models are most successful when they can average over more area and time, increasing accuracy by averaging across heterogeneity. However, the real need is for models to increase in accuracy to the field scale. They emphasized the need to translate guidelines created by models into decision support tools usable by farmers.

- **Impact of Climate-Smart Production Practices on Soil Carbon Levels.** Several participants concluded that while there was potential for greater carbon neutrality and a small carbon drawdown with the adoption of climate-smart practices, bioenergy feedstock systems are unlikely to represent a substantial carbon sink, although they might be effective in decarbonizing production on marginal lands. They cited the complexities of restoring carbon to soils in the context of interactions between nutrient inputs, erosion, and soil production—all these factors contribute to high variability in carbon storage from site to site. Overall, speakers and participants recommended some caution in estimating the capacity of soil carbon storage, the need to consider costs of carbon storage in soils, and finally the value of holistic approaches to soil health that examine broader sustainability.

Research and Development Needs

Breakout sessions explored the question of what research and development is needed to optimize soil carbon storage in bioenergy applications. Participants were broken into groups based on feedstock type, including agricultural residues, dedicated bioenergy crops, and forest material/residues. Feedback provided in breakout sessions is captured in Appendix C. A summary of R&D needs identified by the stakeholders by each feedstock type is given below.

Agricultural Residues. Major areas of research and development needed for agricultural residues include:

- Biochar R&D
    - Determining the best methods of applying biochar to soils.
    - Understanding how biochar properties impact on-field performance.
    - Elucidating correlation between feedstock properties and biochar properties.
    - Understanding how biochar amendments affect soil organic matter content and whether this can be used to justify larger residue removal rates.
    - Developing tools to quantify the impact of biochar on soil carbon and to quantify the permanence of soil carbon storage with management change. In general, accurate measurement of carbon stored in the soil is critical (e.g., through development of sensors for carbon storage and plant growth).
- Experiments/Measurements Concerning Soil Amendments
    - Standardizing soil carbon measurement and verification. Participants emphasized the importance of investigating soil amendments more broadly, including their ability to recycle carbon and nutrients to soil after bioenergy production/post energy production from the removed biomass.

  - Long-term experiments validating assumptions about soil amendment (e.g., biochar, compost, manure) persistence and impacts on mineralization are needed. Federal funding typically is shorter term in nature, and that is insufficient for soil carbon studies.
- Microbiome Effects on Soil Carbon
  - Determining how biotic interactions drive soil carbon storage under varying agricultural management practices. For example, understanding the capabilities of microorganisms to sequester and store carbon in soils (e.g., biostimulants such as methanotrophs and hydrogenotrophs).
  - Assessing impacts of root structure (e.g., depth, architecture, chemical output) on soil carbon storage.
  - Analyzing impacts of microbiome assembly on soil carbon storage.
  - Relating microbiome traits to carbon use efficiency.
- Other R&D Needed
  - Determining the maximum allowable residue removal to still improve soil health while accounting for factors such as type of soil, crop, and climate.
  - Pulsing nutrient-rich material deeper into the soil without disturbance (including vermicompost, biochar, deeply rooted plants, secondary/primary minerals) and assessing its stability/permanence.
  - Studying uptake of heavy metals or other contaminants in plants from biochar.
  - Examining the role deep soil plays in agricultural soil carbon storage. Must manage both organic and inorganic carbon to maintain soil health.

Dedicated Energy Crops. Major areas of suggested research and development into dedicated bioenergy crops included:

- Marginal Soils R&D
  - Studying crops that can transform marginal soil into arable land.
  - Understanding yield potentials for dedicated perennial feedstocks on marginal lands.
  - Broadening the range of potential crops that can grow on truly marginal soils. Related to this, improved crop genetics for perennials and select annuals was emphasized as an important area of investigation, along with improved transformation and breeding strategies.
  - Assessing impacts on biomass quality produced from degraded sites (particularly heavy metals or other mining materials).

- Analyzing broader sustainability impacts in the context of bioenergy deployment on marginal lands.

- Biochar R&D
    - Biochar for soil physico-chemical and biological property improvement and enhanced bioenergy production. Relationships between biochar specification (e.g., pH, ash/mineral content) and on-field performance need to be elucidated.
- Microbiome R&D
    - Engineering/cultivating plant-microbe systems that have aboveground biomass compatibility with bioenergy and bioproduct generation and belowground traits amenable to plant-microbe-soil interactions that enhance carbon sequestration. It was also noted that most bioenergy feedstock research focuses on the chemistry of the aboveground biomass, with little information available on what is happening belowground. For example, the balance with belowground photosynthate allocation, the architecture and chemical recalcitrance of the root system, and symbiotic relationships with fungi that can increase aggregation were all suggested as needed areas of R&D. Related to this, understanding nutrient and metabolic flux between crops, the soil microbiome, and soil minerals was stated as an important research gap.
- Other R&D
    - Updated understanding of the role of biomass chemistry (e.g., lignin, suberin) in soil organic matter formation.
    - Valuation of ecosystem services (e.g., N_2O emissions reduction, water quality improvement) for dedicated energy crops.
    - Understanding and manipulating nitrogen biocycles, as nitrogen has the largest impact on CI of biofuels production.
    - Improved understanding of deep soil carbon sequestration.

Forestry and Woody Biomass. Major areas of research and development needed for agricultural residues include:

- Management Practices
    - Better elucidated connections between specific management practices and soil carbon storage benefits to encourage adoption.
    - Modeling improvements, including the need for more data on soil carbon and LCAs that assess the effect of forest management practices on carbon sequestration, as well as the trade-off of biomass utilization for bioenergy, bioproducts, and harvested wood products.
    - Measuring general impacts of forest thinning and the relationship to soil management, including looking at trade-offs in terms of forest thinning to reduce

wildfire risk and greenhouse gas emissions versus impacts on soil health in terms of disturbance that can increase solar radiation, oxidation, and compaction.

    - Studying site preparation and managing competition early in replanting sites.

- Soil Carbon Testing and Accounting
    - Developing methods that allow for large-scale testing of soil carbon content on area, depth, and time scales, along with accurate and uniform quantification methodology.
    - Improving carbon accounting for woody biomass, such as in terms of the Low Carbon Fuel Standard programs.
- Other R&D
    - Determining site remediation strategies for low-quality soils, such as due to former fires or mining activities.
    - Assessing whether biochar is economically feasible to introduce soil amendments with seedling planting.
    - Improving seed genetics for soil carbon sequestration, along with assisted migration of trees adapted to climate conditions (e.g., drought/heat).

All Feedstocks. There were also responses relevant to all feedstocks:

- Social Aspects and Farmer Adoption
    - Performing social studies to better understand the barriers that prevent farmers from adopting new technologies and what types of government policies and programs can help boost farmer adoption. Researching the different support needs of different practitioners (how large farms, small farms, and Indigenous communities can each benefit from soil carbon storage).
    - Better understanding the difference to farmers between receiving payments for carbon credits, ecosystem services, or management practices. Researching social acceptance for using biomass from federal public lands for climate change mitigation on nonfederal lands.
- Other R&D
    - Understanding nutrient and metabolic flux between crops and the soil microbiome, which could include changes in metabolism of individual species as well as transfer of nutrients in various forms between organisms.
    - Studying the long-term soil carbon storage and collateral benefits to food security and natural disaster resistance.

Conclusions

On March 28–29, 2022, BETO hosted the public virtual workshop "Bioenergy's Role in Soil Carbon Storage." Given the recent emphasis of the Biden administration on decarbonizing the transportation, agriculture, and industrial sectors of the U.S. economy, this workshop examined how decarbonization through enhanced soil carbon storage while growing bioenergy crops is possible by discussing challenges and opportunities that affect soil carbon levels. Stakeholders representing academia, industry, the farming community, municipalities, and federal agencies involved in soil carbon storage participated in this workshop. A series of keynote presentations, plenary presentations, and stakeholder input sessions provided opportunities for sharing knowledge and identifying R&D needs for future advances in soil carbon storage in relation to bioenergy crops.

Climate-smart production practices, such as omitting tillage, deploying cover crops, and applying biochar, are becoming more popular to enhance soil carbon storage. When these practices are applied in concert with the growing of deep-rooting, perennial bioenergy crops that minimize inputs, larger reductions in carbon intensities can be realized through enhanced soil carbon storage compared to traditional crops. Reducing the carbon intensity of feedstocks will in turn reduce the carbon intensity of the biofuels and bioproducts derived from them.

The keynote presentation speakers provided an overview of the importance of soil carbon to combat increasing atmospheric carbon levels due to fossil fuel use and soil degradation. The need for negative-emission agriculture was emphasized, which reduces carbon emissions from farm operations and sequesters the carbon in soils, trees, and wetlands to mitigate climate change. Overall, a key conclusion of the workshop is that R&D is needed to better understand how to leverage soil carbon storage to produce lower-carbon-intensity biofuels.

There were six technical sessions: (1) Mechanisms of Soil Carbon Storage, (2) Management Strategies to Optimize Soil Carbon Storage, (3) Agricultural Management Practices to Optimize Soil Carbon Storage, (4) Forest Management Practices to Optimize Soil Carbon Storage, (5) Research and Development Needed to Support Policy for Soil Carbon Storage in Bioenergy, and (6) Tools for Decision Making in Bioenergy and Soil Carbon Storage. The panelist presentations, as well as the diverse stakeholder perspectives gathered in breakout sessions, provided workshop participants with a shared understanding of the state of soil carbon levels as affected by management practices and edaphic factors. Group discussion further enabled cross-pollination of ideas. A summary of each technical session is given below:

1. The Mechanisms of Soil Carbon Storage session addressed the edaphic factors that affect the rates of soil carbon storage, as influenced by soil texture and mineralogy, and explained the uncertainty and variability often observed in storage estimates. The workshop participants recognized that further R&D is needed to understand the plant-microbe-soil interactions that are necessary to enhance carbon sequestration.

2. The Management Strategies to Optimize Soil Carbon Storage session addressed how climate-smart production strategies might be applied to bioenergy systems, including possible maximum storage capacity of soils for soil carbon. The workshop participants recognized that further R&D should include long-term experiments to validate assumptions about soil amendment (e.g., biochar, compost, manure) persistence and impacts on mineralization. In addition, tools to quantify the impact of biochar on soil carbon and to quantify the permanence of soil carbon storage with management change are necessary.
3. The Agricultural Management Practices to Optimize Soil Carbon Storage session addressed the importance of long-term data sets, management, and edaphic factors in soil carbon storage in bioenergy systems. Speakers identified that significant variability exists across sites and soil fractions. The workshop participants recognized that further R&D should include how biochar amendments affect soil organic matter contents and whether this can be used to justify larger residue removal rates, while accounting for differences in soil, crop, climate, etc. In addition, standardization of soil carbon measurement and verification is necessary to compare soil carbon levels across sites.
4. The Forest Management Practices to Optimize Soil Carbon Storage session addressed a wide range of topics, from the role of woody energy crops in carbon storage to forest management for overall decarbonization. Short-rotation coppiced willow was shown to increase soil carbon in deep soils, but longer-term studies may be required to reduce uncertainty. Biochar was suggested as an opportunity to return carbon to managed forest systems. The workshop participants recognized that future R&D should include more life cycle analysis to assess the effect of forest management practices on carbon sequestration, as well as the trade-off of biomass utilization for bioenergy, bioproducts, and harvested wood products. In addition, future R&D should examine the trade-offs of forest thinning to reduce wildfire risk and greenhouse gas emissions versus impacts on soil health in terms of disturbance that can increase solar irradiation, oxidation, and compaction.
5. The Research and Development Needed to Support Policy for Soil Carbon Storage in Bioenergy session focused on needed investments in research and development to support policies to promote soil carbon storage in bioenergy. Biochar research was emphasized, as well as tools for quantifying soil carbon. Focusing on holistic practices that promote overall soil health was also emphasized.
6. The Tools for Decision Making in Bioenergy and Soil Carbon Storage session highlighted systems, frameworks, and models that are enabling better measurement and verification of soil carbon storage by bioenergy systems. These included the SYMFONI project, which holistically tracks carbon budgets across farm fields, updates to CENTURY-based models with county-level carbon budget capabilities, and advances in process-based models to move beyond DAYCENT-derived parameters toward new paradigms such as MEMS and Cycle.

Overall, workshop participants supported the concept that soil carbon storage and biofuel production could work synergistically. Increasing soil carbon storage improves the health of the soil and can result in higher-yielding bioenergy crops, which in turn can produce lower-carbon-intensity biofuels. Many areas of R&D were identified during the workshop, and participants emphasized the need for long-term studies that give reliable field data. Application of soil amendments such as biochar could potentially lead to long-term soil benefits, but considerable applied R&D is necessary to fully correlate biochar properties and performance. The information and feedback gathered at this workshop will help DOE address the most critical barriers to reducing carbon intensity of feedstocks for biofuels and bioproducts through enhanced storage of soil carbon. DOE's Bioenergy Technologies Office would like to thank all of the participants for their valuable input.

Appendix A: Agenda

Agenda: Bioenergy's Role in Soil Carbon Storage

U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO)
March 28–29, 2022. All times EST

Monday, March 28				
9:30 am	***Workshop Opening***			
	Welcome		Nichole Fitzgerald, DOE BETO Valerie Reed, DOE BETO Mark Elless, DOE BETO	
	Stakeholder Questions and Introduction to XLeap			
10:00 am	***Highlights from Previous Federal Programs on Soil Carbon and Current Agency Perspectives/Directions***			
10:04 am	Engineering and Managing Terrestrial Ecosystems for Optimized Carbon Dioxide Removal and Negative Emissions Pathways		David Babson, DOE, ARPA-E	
10:16 am	Microbiome Research for Carbon Cycling and Sustainable Bioenergy Feedstocks in BER's Genomic Science Program		Boris Wawrik, DOE, Office of Science, Biological and Environmental Research	
10:28 am	USDA Soil Carbon Research and Management		Sandeep Kumar & Vance Owens, USDA	
10:48 am	The Recent Evolution of Sustainability Research as NSF in Relation to Soil Science and Engineering		Brandi Schottel, NSF	
11:00 am	Presentation Question & Answer Session, Mediated via XLeap			
11:15 am	***Virtual Lunch Break:* Open Networking Session via XLeap**			
12:00 pm	***Keynote Talk:*** Negative Emission Farming and Soil Carbon Sequestration		Rattan Lal, Director Rattan Lal Center for Carbon Management and Sequestration, Ohio State University	
	Presentation Question & Answer Session, Mediated via XLeap			
1:00 pm	***Mechanisms of Soil Carbon Storage***		***Management Strategies to Optimize Soil Carbon Storage***	
1:03 pm	Factors Affecting Organic Carbon Stability/Sequestration in Agricultural Soils	Keith Paustian, Colorado State University	Systems Perspectives on Carbon Storage by Bioenergy Crops	Tom Richard, Penn State University
1:17 pm	The Efficacy of Amelioration Practices for Crop Residue Removal in the Western Corn Belt	Virginia Jin, USDA-ARS	Quantifying Climate-Smart Agriculture Management Impacts on Soil Carbon Storage and Greenhouse Gas Emissions at Multiple Scales	Wei Ren, University of Kentucky
1:31 pm	Biochar Impact on Soil Carbon Sequestration and Sustainability of Crop Residue Harvesting for Bioenergy	David Laird, Iowa State University	Carbon Farming: How Plant Roots, Microbial Ecophysiology, and Soil Minerals Shape the Fate	Jennifer Pett-Ridge, Lawrence Livermore National Laboratory

			and Persistence of Carbon in Bioenergy Systems	
1:45 pm	Stakeholder Input Breakout Sessions, Mediated via XLeap			
2:50 pm	***Break***			
3:00 pm	***3 × 5 Stakeholder Lightning Talks***			
3:55 pm	***Adjourn***			
Tuesday, March 29				
9:30 am	***Virtual Coffee Hour:*** **Open Networking Session in XLeap**			
10:30 am	***Welcome and Second Day Opening***		Asmeret Asefaw Berhe, UC Merced	
10:55 am	***Agricultural Management Practices to Optimize Soil Carbon Storage***		***Forest Management Practices to Optimize Soil Carbon Storage***	
10:58 am	Not All Soil C is Made Equal: How Biofuel Crops May Increase Particulate or Mineral Associated Organic Matter	Francesca Cotrufo, Colorado State University	Importance of Soil Carbon and Belowground Biomass on GHG Balance in Willow Biomass Crops	Tim Volk, SUNY ESF
11:13 am	Potential for Carbon Accrual in Bioenergy Feedstock Fields	Kirsten Hofmockel, Pacific Northwest National Laboratory	Sustainable Forest Management for Increasing Soil Carbon Sequestration with Biochar	Carlos Rodriguez Franco, U.S. Forest Service
11:28 am	Soil Carbon Sequestration by Switchgrass: Potential and Management	Mark Liebig, USDA-ARS	A Circular Forest and Biomass Energy Decarbonization System for Bioeconomy	Jingxin Wang, West Virginia University
11:43 am	Stakeholder Input Breakout Sessions, Mediated via XLeap			
1:00 pm	***Virtual Lunch Break:*** **Open Networking Session in the Wonder Platform**			
2:00 pm	***Research and Development Needed to Support Policy for Soil Carbon Storage in Bioenergy***		***Tools for Decision Making in Bioenergy and Soil Carbon Storage***	
2:04 pm	Research Priorities in Soil Health and Carbon Storage for Production of Bioenergy Crops	Cristine Morgan, Soil Health Institute	SYMFONI - A "System-of-Systems" Solution to Quantify Carbon Outcome for Bioenergy Feedstock Production at the Field Level	Kaiyu Guan, University of Illinois at Urbana-Champaign
2:16 pm	Realizing Soil Carbon Sequestration: Research Gaps in the Context of Biofuels	Ronald Amundson, UC Berkeley	Soil Organic Carbon Modeling to Support a Feedstock-level Biofuel Life Cycle Analysis	Hoyoung Kwon, Argonne National Lab
2:28 pm	Biochar at the Interface of Energy Transition and Regenerative Agriculture	Ghasideh Pourhashem, Genomatica & Elsie Hung, Rice University	Assessing the Role of Soils in Carbon-Negative Bioenergy Landscapes	John Field, Oak Ridge National Lab
2:40 pm	Presentation Question & Answer Session, Mediated via XLeap			
3:10 pm	***Final Stakeholder Input Breakout Sessions, Mediated via XLeap***			
3:50 pm	***Adjourn***			

Appendix B: Participant List

Last Name	First Name	Organization	Job Title
Abramoff	Rose	Oak Ridge National Laboratory	Associate Scientist
Adamson	Harry	Pennsylvania State University	Ph.D. Student
Adhikari	Sushil	Auburn University	Professor
Adler	Paul	USDA-ARS	Research Agronomist
Ahmadzadeh Araji	Hamidreza	Texas A&M AgriLife Research & Extension center	Postdoctoral research associate
Ahrens	Toby	USDA, National Institute of Food and Agriculture	National Program Leader
Albert	Ambrose	Student Energy	Student
Alexiades	Anthy	CARB	Air Resources Engineer
Allen	Jan	Impact Bioenergy Inc	Pres
Allen	Trip	Levitree	President
Amonette	Jim	Pacific Northwest National Laboratory	Senior Research Geochemist
Amundson	Ronald	UC Berkeley	Professor
Anderson	Murray	M.L. Anderson Advisory Service	President
Anderson	Neil	Poet	VP Business Development
Anderson	Paul	Woodgas Pyrolytics Inc	President and CEO
Anderson	Ruth	Natural Resources Conservation Service	Resource Soil Scientist
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Appendix C: Stakeholder Feedback from Breakout Sessions

Breakout sessions gathered stakeholder input and were organized by feedstock type, specifically (1) agricultural residues, (2) dedicated bioenergy crops, and (3) forest materials/residues. Breakout sessions for the three feedstock topics were run concurrently, and participants chose their breakout session based on their expertise and interest. In the first breakout session, participants were asked to rank the following climate-smart agricultural practices according to metrics of significance to soil carbon storage: agroforestry, buffer strips, cover crops, enhanced-efficiency fertilizers, legume interseeding, low-till or no-till, microbiome (including engineered), nutrient management, planting for high carbon sequestration rate, seed genetics, and soil amendments (e.g., biochar). The specific questions were:

1. What is the short-term impact of different climate-smart agricultural practices to soil carbon storage (i.e., over the course of 5 years of continuous implementation)?
2. What is the long-term impact of different climate-smart agricultural practices to soil carbon storage (i.e., over the course of 50 years of continuous implementation)?
3. What is the effect of different climate-smart agricultural practices on persistence of soil carbon storage (assuming a halt in implementation after 5 years)?
4. What is the likelihood of success, spanning from R&D technical achievements through adoption, for different climate-smart agricultural practices?

Participants highlighted cover crops and soil amendments as having high likelihoods of adoption, while enhanced-efficiency fertilizers were expected to have lower adoption (all rankings displayed in table below). Short-term carbon storage was anticipated to be highest for transitions to low- or no-till agriculture/energy crop systems, and for the addition of biochar or other soil amendments across forests, agricultural, and energy crop systems. Seed genetics were expected to have the least short-term impact on soil carbon storage, and greater impacts were expected in energy crops and agriculture than forest systems. For long-term soil carbon storage, biochar again emerged as the most substantive impact, along with cover crops, low- or no-till crops, and agroforestry. Management practices expected to have low long-term impact included seed genetics, buffer strips, and nutrient management. Legume interseeding was expected to be relatively low impact. Enhanced-efficiency fertilizers were expected to be effective in forest but not agricultural systems. Persistence was expected to be highest in biochar, although participants discussing energy crops rated it as lower persistence. Management of the microbiome and agroforestry were rated as having high persistence, particularly in forests. Cover crops, legume interseeding, and enhanced-efficiency fertilizers were expected to have the lowest persistence, especially in agricultural systems.

Participant ranking of climate-smart management strategies in relation to soil carbon storage based on four queries: (1) likelihood of success, spanning from R&D technical achievements through adoption; (2) short-term impact to soil carbon storage (over the course of 5 years of continuous implementation); (3) long-term impact to soil carbon storage (over the course of 50 years of continuous implementation); and (4) persistence of soil carbon storage (assuming a halt in implementation after 5 years). Rankings were made for forest residues, energy crops, and agricultural residues. 0 = no impact, 5 = some impact, and 10 = max impact.

Climate-Smart Practices	Query	Forest Residues (mean, SD)	Energy Crops (mean, SD)	Ag Residues (mean, SD)
Agroforestry	Likelihood of success	6.85 ± 0.12		6.68 ± 0.19
	Short-term impact	5.43 ± 0.15		4.96 ± 0.22
	Long-term impact	7.14 ± 0.17		7.87 ± 0.15
	Persistence	6.5 ± 0.2		6.1 ± 0.24
Buffer strips	Likelihood of success		6.71 ± 0.22	6.53 ± 0.18
	Short-term impact		5.8 ± 0.19	5.37 ± 0.2
	Long-term impact		6.72 ± 0.22	6.42 ± 0.17
	Persistence		5.48 ± 0.25	5 ± 0.21
Cover crops	Likelihood of success			7.62 ± 0.13
	Short-term impact			5.88 ± 0.24
	Long-term impact			7.58 ± 0.17
	Persistence			4.96 ± 0.22
Enhanced-efficiency fertilizers	Likelihood of success	5.5 ± 0.23	6.36 ± 0.22	6.4 ± 0.23
	Short-term impact	5 ± 0.15	5.76 ± 0.2	5.45 ± 0.23
	Long-term impact	6.42 ± 0.2		6.79 ± 0.23
	Persistence	5.73 ± 0.23	4.69 ± 0.29	4.21 ± 0.27
Legume interseeding	Likelihood of success			6.55 ± 0.18
	Short-term impact			5.4 ± 0.18
	Long-term impact			6.65 ± 0.18
	Persistence			5.32 ± 0.23
Low-till or no-till	Likelihood of success		7.2 ± 0.21	7.12 ± 0.25
	Short-term impact		6.34 ± 0.24	6.67 ± 0.25
	Long-term impact		7.17 ± 0.26	7.7 ± 0.24
	Persistence		5.91 ± 0.3	5.68 ± 0.31
	Likelihood of success	7.22 ± 0.2	6.03 ± 0.22	6.43 ± 0.23

Climate-Smart Practices	Query	Forest Residues (mean, SD)	Energy Crops (mean, SD)	Ag Residues (mean, SD)
Microbiome (including engineered)	Short-term impact	7.38 ± 0.14	5.47 ± 0.25	6.24 ± 0.22
	Long-term impact	7.78 ± 0.17	6.67 ± 0.25	7.38 ± 0.23
	Persistence	7.22 ± 0.23	6.07 ± 0.24	6.6 ± 0.26
Nutrient management	Likelihood of success	5.67 ± 0.26	6.7 ± 0.19	6.77 ± 0.21
	Short-term impact	5.3 ± 0.16	6.03 ± 0.2	5.64 ± 0.21
	Long-term impact	6.7 ± 0.23	6.79 ± 0.17	6.55 ± 0.19
	Persistence	5.9 ± 0.25	5.82 ± 0.22	5.24 ± 0.24
Planting for high carbon sequestration rate	Likelihood of success	7 ± 0.15	6.56 ± 0.16	6.08 ± 0.21
	Short-term impact	5.6 ± 0.19	6.31 ± 0.21	5.73 ± 0.27
	Long-term impact	7.47 ± 0.16	7.31 ± 0.19	6.6 ± 0.2
	Persistence	6.73 ± 0.19	6.09 ± 0.2	5.46 ± 0.26
Seed genetics	Likelihood of success	6.9 ± 0.23	5.81 ± 0.2	6.43 ± 0.26
	Short-term impact	4.33 ± 0.19	5.27 ± 0.22	5.33 ± 0.24
	Long-term impact	6.7 ± 0.21	6.54 ± 0.18	6.55 ± 0.23
	Persistence	6.78 ± 0.22	5.27 ± 0.23	5.4 ± 0.24
Soil amendments (e.g., biochar)	Likelihood of success	8.07 ± 0.16	6.85 ± 0.21	7.46 ± 0.24
	Short-term impact	6.53 ± 0.21	6.5 ± 0.19	7.19 ± 0.22
	Long-term impact	8.2 ± 0.14	6.76 ± 0.22	7.85 ± 0.19
	Persistence	8 ± 0.17	6.29 ± 0.21	8.2 ± 0.19

In the next breakout session, the following question was asked of the attendees in all breakout groups so that feedstock-specific responses could be gathered for the same reason as for the first two sessions:

1. What R&D is needed to optimize soil carbon storage in bioenergy applications?

A variety of responses were discussed in the breakout sessions, and the top responses for each feedstock type are highlighted in bullets below. Major themes emerged—for instance, the need for improved tools to measure and monitor soil carbon consistently across feedstock types. Biochar and other soil amendments was another topic area discussed commonly in the breakout sessions.

Agricultural Residues

- Understanding of how biochar amendments affect soil organic matter and whether its application can be used to justify larger residue removal rates.

- Long-term experiments to validate impacts of amendment and management strategies on soil carbon content. Biochar was especially highlighted as a soil amendment.
- Quantification of soil carbon permanence during land management changes.
- Relation of root structure, microbiome assembly, and microbiome traits to carbon use efficiency.
- Availability of tools for measurement and monitoring soil carbon, development of sensors.

Dedicated Bioenergy Crops

- Development of bioenergy crops that can transform marginal soils to arable land.
- Robust data collection on deep soil carbon sequestration.
- Understanding nutrient and metabolic flux between crops and soil microbiome.
- Improved tools for measuring and monitoring soil carbon and on-farm demonstrations to experimentally validate predicted soil carbon storage.
- Biochar for soil physio-chemical and biological property involvement and enhanced bioenergy production.

Forest Materials/Residues

- Improved, uniform soil carbon quantification methods that can make monitoring and verification accurate, easy, low cost, and large scale.
- Forest thinning for fire reduction and relationship to soil management.
- Site remediation for low-quality soils (e.g., post-fire areas, mining remediation).

After the session, attendees were asked the following questions as it pertained to the top R&D responses per feedstock type:

1. What metrics for success or performance would indicate successful research and development in the top areas of need?
2. What opportunities or challenges do these needs present for community partnerships and/or diversity, equity, inclusion, and justice initiatives?
3. What trade-offs between feedstock yield and soil carbon storage do you anticipate for production of agricultural residues, and what are the best strategies to address them?
4. What unique circumstances apply to managing bioenergy production for soil carbon storage?

Responses to these questions are displayed in bullets below.

Metrics for Success or Performance

- Increased soil carbon content and improved agronomic productivity, water use efficiency, nutrient use efficiency, carbon use efficiency, and soil structure.
- A decision support tool that helps to customize biochar based on site factors and expected outcomes.
- Socioeconomic information on the likelihood of a farmer to maintain constant land management indefinitely, as well as an understanding of the cost of carbon sequestration versus the cost of avoided emissions if funds are invested in other renewable energy technologies, through LCA/techno-economic analysis studies.
- Standardized and sensitive sensors and development of GIS models that help monitor soil carbon.
- Scaling lab studies appropriately to inform the impact of amendment additions for field studies.
- Recognition of full benefits and costs of management alternative (e.g., ecosystem services).
- Demonstrated restoration of marginal lands.

Opportunities or Challenges

- Better integration of energy research with agronomic research in terms of biochar production and performance and development of beneficial land use decisions.
- Private-public partnerships with companies that are vertically integrated into carbon credit markets. Companies can use their financial incentives to measure soil carbon, implement management strategies, and bring new landowners into carbon sequestration. Tools for measuring soil carbon must be kept low cost for wide farmer adoption, perhaps making monitoring and verification free for minor and underrepresented communities.
- Small-forest data need to be aggregated to make them meaningful for small landowners.
- Affordably converting forest thinnings into chips could help forest owners reduce fire risk while also providing these chips to landowners who cannot afford more expensive soil amendments (e.g., biochar or fertilizer).
- Look at the cost/benefits of residue removal/utilization in comparison to slash pile burnings.
- Ensure that bioenergy systems do not jeopardize food production/sovereignty, especially food for marginalized communities.
- Restoration of marginal/degraded agricultural land provides an opportunity for both adding economic value to the land and increasing future food production potential.
- Broaden range of potential crops that can grow on marginal soils.
- Cost and profit sharing in terms of carbon accounting is important for local community involvement.
- Communication with marginalized and disadvantaged communities from the outset is essential.

Trade-Offs between Feedstock Yield and Soil Carbon Storage

- Harvesting bioenergy crops can negatively impact soil carbon storage. Therefore, best practices need to be established for optimizing harvest of bioenergy crops while not depleting soil carbon and overall soil health over multiple years. Carbon impacts of keeping residues on the field versus collecting them and converting to biochar also need to be quantified. Similarly, must understand balance between biochar quality and biofuel yield.
- Breeding for harvested biomass quality versus belowground carbon persistence is a significant trade-off.

- Need to know the trade-off between carbon loss of residues left on the field versus collecting the residues and converting them to biochar. Trade-offs are likely to be largest in intensive management systems.
- There is an assumption that increased yield results in increased soil organic carbon, but this needs to be proven.
- Understand relationship between root exudates on crop yields and the microbiome.
- Verify if increasing soil carbon improves the feedstock end use. May need to reexamine whether maximizing aboveground biomass yield affects long-term soil carbon storage.

Unique Circumstances to Managing Bioenergy Production for Soil Carbon Storage

- Local sources for biochar production need to be mapped.
- Many landowners own small parcels but want to manage their land to optimize carbon with a very small forest product component.
- Challenges remain for providing incentives to undertake thinnings and how to deal with the removed material.
- Need to recognize different time scales of management systems between agricultural crops and forests; forests functioning on smaller time scales struggle.
- The cost of perennial establishment, especially in marginal lands, should be considered.
- The permanence of soil organic carbon if land management changes needs to be considered.
- There is difficulty in quantifying deep soil carbon, and questions remain whether such deep soil carbon is more stable and has more value than surface, labile carbon.
- Need to understand how stored carbon affects its availability to feedstocks for both energy production and food sources.
- For perennial energy crops, a unique challenge is the long-term nature of these systems and the final disposition/permanence of the soil carbon.
- Need to build our understanding of new management systems employed when growing bioenergy crops for the first time.

Follow-up breakout sessions allowed participants to discuss the R&D needed to optimize soil carbon storage in bioenergy applications. Biochar received extensive discussion across five of the six breakouts and across all three feedstocks (agricultural residues, forest residues, and bioenergy) discussed. The ability to effectively measure, monitor, and verify soil carbon storage was also discussed across five breakouts and in all three feedstock topic areas. Sessions focused on bioenergy crops and forest residues expressed interest in remediation and use of marginal lands. The permanence and persistence of soil carbon was of particular interest to those groups discussing agricultural residues and bioenergy crops.

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DOE/EE-2695 · March 2023

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