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Scaling Sustainable Biochar Research & Commercialization for Agriculture & Conservation:

A Summary from a Stakeholder Convening

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Executive Summary

Biochar is a carbon-rich substance with the potential to increase soil carbon sequestration, reduce greenhouse gas (GHG) emissions and improve soil health. When used as part of soil health management systems, biochar can provide multiple synergistic benefits for the agricultural sector and society, while also supporting the production of renewable, climate-neutral biofuels. Establishing a pyrolysis biochar bioenergy industry (PBBI) is necessary to harness the environmental benefits of biochar. To galvanize the necessary coordination to support a PBBI, the Foundation for Food & Agriculture Research (FFAR), the National Center for Appropriate Technology (NCAT), and American Farmland Trust (AFT) co-hosted a virtual convening event on biochar research and commercialization in March 2022. Participants represented a diverse set of stakeholders, including biochar producers, agricultural producers, and members of nonprofit, industry and government agencies. This whitepaper offers a summary of the convening, as well as insights from subsequent stakeholder engagement.

Sustainably sourced, fit-for-purpose biochar can be a powerful tool in the soil health management systems and climate-smart toolbox, with decades of research supporting soil, environmental, production, and climate benefits. However, because biochar represents a range of feedstocks, processes and products, there is a critical need to:

- Coordinate efforts to characterize and test the application of biochar types across locations with diverse soil and management conditions
- Address research and decision-support gaps
- Support the growing industry

These objectives can be addressed or advanced through a coordinated strategy. To support establishment of this strategy, the convening participants identified key gaps in implementation and research. The experiences of foresters, ranchers, and farmers already using biochar, some of whom participated in the convening, helped inform priorities. Key gaps include:

- Cross-site fundamental research on different biochars and soils effects on soil health, productivity, greenhouse gas emissions, and carbon sequestration
- Practical, applied on-farm research
- Maximum benefits for conservation
- Decision support
- Life Cycle Assessment (LCA)

Existing research gaps include:

- Potential synergies among biochar, soil organic matter, and enhanced rock weathering
- Development of new storage reservoirs for biochar in industrial products

Convening participants further provided next steps for rapidly developing a PBBI to produce sustainable, fit-for-purpose biochars that increase soil health and mitigate climate change. Participants also stressed the need for actionable, coordinated, large-scale research relevant to commercial production in the next five years. To have a chance to reduce greenhouse gas emissions, we need an array of tools that would aid in mitigation; a coordinated strategy to enable biochar to be an effective tool in the soil health and climate smart toolbox must be created. We cannot wait 50 years.

Section 1. Introduction

Biochar, a charcoal-like substance most often produced through pyrolysis, which converts organic materials under low oxygen and high temperature conditions (400 – 600ºC) into highly stable carbon compounds that remain in soils for hundreds to thousands of years. Biochar can increase carbon sequestration and reduce greenhouse gas (GHG) emissions. As part of soil health management systems, biochar can build healthy, high-functioning soils and more resilient agroecosystems, while supporting sustainable biofuel production that partly off-sets fossil fuels. When added to soil, some biochars persist with a mean residence time measured in centuries. Additionally, sustainably sourced, fit-for-purpose, appropriately implemented biochar can provide many ecosystem services, including enhanced productivity and reduced emissions of nitrous oxide (N_2O) and methane (CH_4).

However, there are significant gaps in the biochar knowledge base and market viability due to the diversity of feedstocks, biochar production methods, and the heterogeneous response to diverse biochars of agricultural, horticultural, silvicultural, and rangeland systems across soils and climates. These knowledge gaps must be addressed before the economic and environmental benefits of biochar can be fully realized. Unfortunately, filling these knowledge gaps is difficult due to short research funding cycles and the lack of a comprehensive, coordinated national biochar research program. To reach its full potential, biochar research requires substantial funding and a coordinated strategy. Such a research strategy must include federal, state, and local governments as well as nonprofits and the private sector to build on the current momentum toward soil health management and climate smart systems. Additionally, while biochar has been modernized through the refinement of pyrolysis, the commercialization of a pyrolysis industry has been limited.

To galvanize the necessary coordination to support a pyrolysis biochar bioenergy industry (PBBI), on March 29 – 30, 2022, the Foundation for Food & Agriculture Research (FFAR), the National Center for Appropriate Technology (NCAT), and American Farmland Trust (AFT) co-hosted a two-day virtual convening on biochar research and commercialization. The first day of the convening discussed the recent publications co-authored by speakers and organizers of the event, including the Integrated Biochar Research: A Roadmap[1] and Biochar in Climate Change Mitigation[2]. Conversations on the second day engaged industry partners to assess policies and investments needed to develop a sustainable PBBI. The convening addressed the following objectives:

- Develop consensus on a public and private strategy to address biochar knowledge gaps
- Identify structure, players, and funding needed to address research needs
- Identify key steps, stakeholders, and participants for commercialization of pyrolysis-based biofuels and biochar

The convening brought together 35-45 invitation-only diverse stakeholders each day, including biochar producers, agricultural producers, and members of nonprofit organizations, industry, and government agencies. Stakeholders concluded that a PBBI must be built to realize biochar's potential benefits for soil health and carbon sequestration at scales large enough to impact climate change and the health of agriculture and forestry ecosystems. The following report includes a summary of the convening, as well as stakeholder insights and proposed next steps to achieve this goal.

Section 2. Convening Day 1

Biochar & its Role in Soil Health & Climate Change

Biochar is a vital tool in the soil health management systems and climate-smart toolbox that increases total soil carbon and various soil functions. Particularly for eroded or otherwise degraded soils, biochar can improve soil health, yield, and crop resilience to extreme weather.[3-6] Decades of research results have reflected variations in outcomes across biochars, soils, climate, and application and management practices. Hence, there is a critical need for a coordinated large-scale research program that characterizes and tests the application of a range of biochar types across multiple locations with diverse soil and management conditions to enable targeted management for maximized benefits.

Biochar holds unique promise for building soil carbon because, unlike biomass or manure carbon, biochar carbon can persist in soils for hundreds to thousands of years. In addition, sustainably sourced fit-for-purpose biochar amendments can lower GHG emissions by decreasing nitrous oxide emissions from soils,[7,8] methane emissions from rice paddies,[9] and in some instances, methane emissions from ruminant livestock when added to high roughage diets.[10] Biochar can slow the breakdown of native soil organic carbon by a process known as negative priming, possibly through adsorption or physical protection of organic carbon,[3,6] further increasing soil carbon sequestration and complementing other soil health management practices. Biochar can provide additional water and air quality benefits such as reduced phosphorus and nitrate losses, and ammonia volatilization.[11,12]

Equally important, biochar can offer real economic and environmental benefits to farmers, ranchers, and foresters.

Equally important, biochar can offer economic and environmental benefits to farmers, ranchers, and foresters. When produced, characterized, and managed correctly, biochar can improve soil health, increase crop yields and enhance forest reestablishment on marginal and degraded soils. Except in instances where biochar and soil properties were not well matched, biochar application to soil at levels up to about 50 tonnes per hectare (23 tons per acre) either does no harm or increases crop yields and quality.[13] In some instances (highly acidic or degraded soils) the productivity improvements are significant, with average increases on the order of 5-20%.[17,26,30,59] Biochars have also been shown to be effective at enhancing nutrient efficiency when combined into novel fertilizer products.[14]

Our general scientific understanding suggests that productivity improvements come from a combination of improved:

- soil physical properties (improved aeration, increased porosity, lower bulk density, increased water infiltration rates and plant-available water-holding capacities); and
- chemical properties (nutrients provided by the biochar, increased nutrient-retention capacities, and increased pH of acidic soils); and
- microbiological properties (enhanced mycorrhizal fungi activity, microbial carbon use efficiency and biological fixation of nitrogen).[4,13]

Further, biochar can enhance climate resilience, enabling farms and ecosystems to reduce risk and endure extreme weather by capturing and storing more water during heavy downpours, which can sustain crops and forests through heat waves and droughts. On-farm economic studies relevant to diverse commercial farming operations are limited, especially those that account for co-benefits and other ecosystem services. This gap needs to be addressed to facilitate commercially viable biochar adoption in agriculture.

To maximize biochar's potential, stakeholders must understand which types of biochar achieve the desired results in varying soils, climates, and production systems, as well as how to characterize and cost-effectively generate, select, and utilize these fit-for-purpose biochar products. Research can also support developing an industry to sustainably produce, transport, and use biochar and biofuel coproducts, and to standardize biochar production and characterization methods. This new industry must be built at a pace sufficient to meet the challenges resulting from climate change. Convening participants stressed the need for actionable, coordinated, large-scale research results that are relevant to commercial production in the next five years. To have a chance to reduce greenhouse gas emissions, we need an array of tools that would aid in mitigation; a coordinated strategy to enable biochar to be an effect tool in in the soil health and climate-smart toolbox must be created. We cannot wait 50 years.

State of the Science, Research Needs, & Gaps

Biochar is a spectrum of materials that can have different properties and thus different impacts. Thus, the existing biochar research has great variability and when considering the current literature, stakeholders must consider the subtle differences among studies.

The complexity of effects can be further explained as a consequence of *Soil type X Crop X Management X Weather X Biochar type (SCMWB)* interactions that influence both agronomic and environmental outcomes. Despite these complexities, a broad consensus is emerging in the scientific literature on the benefits of soil biochar amendments when carefully selected and appropriately applied to each unique soil, climate, and production system.[15] These areas of consensus are:

1. Biochar is effective for sequestering carbon in soils (half-life of biochar carbon can significantly exceed 100 years for biochars produced at pyrolysis temperatures ≥ 500°C);[2,16-18]
2. Biochar amendments can reduce soil bulk density and increase soil porosity;[19-22]
3. Biochar amendments can increase soil water holding capacity (particularly in well and moderately well drained soils);[20,21,23,24]
4. Biochar amendments add to the soil most of the phosphorus, potassium, calcium, magnesium, zinc and micronutrients and about half of the nitrogen and sulfur that are in the biomass feedstock used to make the biochar;[25-29]
5. Many biochars are weak to moderate liming agents that can be prescribed to reduce the agricultural lime needs to maintain soils in the optimum pH range;[30-32]
6. Biochars can provide habitat for soil microorganisms and thereby increase nutrient cycling and other biologically based soil functions that build and cycle carbon and nutrients;[31-34]
7. When implemented for particular purposes, many biochars can be adsorbents of nutrients, pesticides, and various organic and inorganic contaminants;[32,35,36]
8. Biochar amendments can increase the ability of soil to form, retain, and stabilize new soil organic matter, which is derived from other organic inputs to the soil such as crop residues (leaves, stems, and roots) and manure. Negative priming makes biochar an especially synergistic practice when used in combination with other soil health management practices.[3,6,37-39]

The science underpinning biochar technology is diverse and multidisciplinary and mirrors the wide range of feedstocks, conversion methods, products, and storage strategies.[40] Current research needs and gaps include cross-site and site-specific research, and innovative improvements in implementation and quantification of effects. The conversations at the Convening reflected broad agreement on the critical need for applied biochar research, as proposed in Integrated Biochar Research: A Roadmap[1]:

- Cross-site research, common to all sites, to develop fundamental knowledge on the impact of different types of biochar on soil health, productivity, soil carbon sequestration, soil GHG emissions, and economics, including resilience functions such as the soil capacity to absorb heavy downpours and store plant available water for later periods of moisture deficit; and
- Site specific research to develop site specific recommendations and regionally promising systems using local feedstocks, including economic analysis of such systems at varying carbon prices.

Another critical need to move biochar from research to implementation, is excellent decision support tools. Such tools would allow farmers to successfully target specific soil constraints, adapted to their farm's unique parameters, by recommending biochar applications that are appropriate for their individual needs. Recently, biochar modules have been added to cropping system models,[41] but a prescriptive understanding that allows agricultural producers and their advisors to provide specific recommendations for desired outcomes is still very limited. Two existing online decision support toolkits can help farmers pair soil deficiencies with biochar properties to maximize benefits to crops and soils:

- The USDA Natural Resources Conservation Service (NRCS) released the Dynamic Soil Property Response to Biochar SSURGO interpretative tool within Web Soil Survey that predicts the likelihood that a soil will respond positively to biochar amendment.[42]
- In the Pacific Northwest, farmers can use information from Web Soil Survey to harness decision support modules in the Pacific Northwest Biochar Atlas.[43] This online tool allows farmers to match soil deficiencies to biochar properties to increase productivity and decrease economic risk. While this tool is currently limited to soils and biochars specific to Oregon, Washington, and Idaho, a collaboration of government, nonprofit, and university partners are working to expand this decision support toolkit to the entire U.S. in the next two years.

With respect to climate change mitigation, roughly half of the potential impact of biochar stems from storage of carbon, a quarter from offsets of fossil carbon emissions (when energy released during biochar production is used), and the remainder from avoided emissions of biomass decomposition, soil processes, and increases in soil productivity.[44] The minimum estimates of biochar's efficacy range from 0.4 to 1.2 tonnes CO_2-e per dry tonne of feedstock[45-47], but Life Cycle Assessments (LCA) that include post-production applications, (such as co-composting) and alternative biomass fates (such as open burning) can yield values as much as an order of magnitude higher.[48]

LCAs also show that, when biochar is made, a carbon debt is often incurred relative to other potential pathways for the same biomass, and that the manner of production can affect the size of this debt by an order of magnitude. Maximum sustainability is achieved when the carbon debt is retired in less than ten years.[16,48] In addition to alternative fates for the same biomass, key production factors affecting the size of the carbon debt include carbon efficiency (fraction of biomass carbon that is in the biochar produced), emissions of methane and soot during production, stability in soil of the biochar produced, and whether the energy released is captured and used to offset fossil-carbon emissions. Despite the importance of climate offsets, measurements of methane and soot emissions are rarely made, and capture/use of the energy released is usually not performed with small, simple production systems.

The concept of a time-sensitive LCA, and associated carbon debts, is described by Amonette et al. 2021.[15]

> “Life cycle assessments (LCAs) of the climate mitigation impact of biochar technology consider biomass sourcing, transport and processing, biochar production, transport and application, fossil-fuel offsets resulting from energy produced and captured during biochar production, and the subsequent impact of biochar on plant growth and C stocks after application to soil. To quantify the net climate impact, however, a comparable set of emissions associated with the alternative fate of the biomass feedstock (e.g., natural decay, wildfire, land filling, etc.) also needs to be considered. At any point in time, subtraction of the cumulative alternative emissions from the cumulative biochar-technology emissions provides the net climate impact. When the emissions by biochar are lower than the alternative biomass pathway, the net emission are less than zero and the result is termed “C negative.” In general, LCAs have indicated that biochar has a net climate impact of about -0.4 to -1.2 tonnes of CO_2 equivalents per tonne of bone dry feedstock (t CO_2e BD tonne^{-1}), meaning that the climate impact is beneficial (resulting in less CO_2 in the atmosphere). Increases in net emissions are possible with biochar, however, when purpose-grown feedstock is used and indirect land use change is included.[45-47]”
>
> “Because the impact of GHGs changes with time due to their different atmospheric residence times relative to CO_2, the climate impact will also change depending on the period being considered. A time sensitive LCA approach fully captures this dynamic as shown in a hypothetical example for biochar and two alternative biomass fates (Figure 1). In the left panel, total GHG emissions per unit of biomass C are shown for each of the three biomass pathways. The right panel shows the net GHG emissions for biochar relative to the alternative biomass pathways. In this hypothetical example, when biochar is compared to wildfire, it is always C negative. When it is compared with biomass decay, on the other hand, the emissions from biochar production exceed those of biomass decay for a short period. Eventually, cumulative emissions from biomass decay exceed those from biochar production and the net GHG emissions fall into the C-negative region. The period between biochar production and achievement of C negativity is termed the C-payback period.”

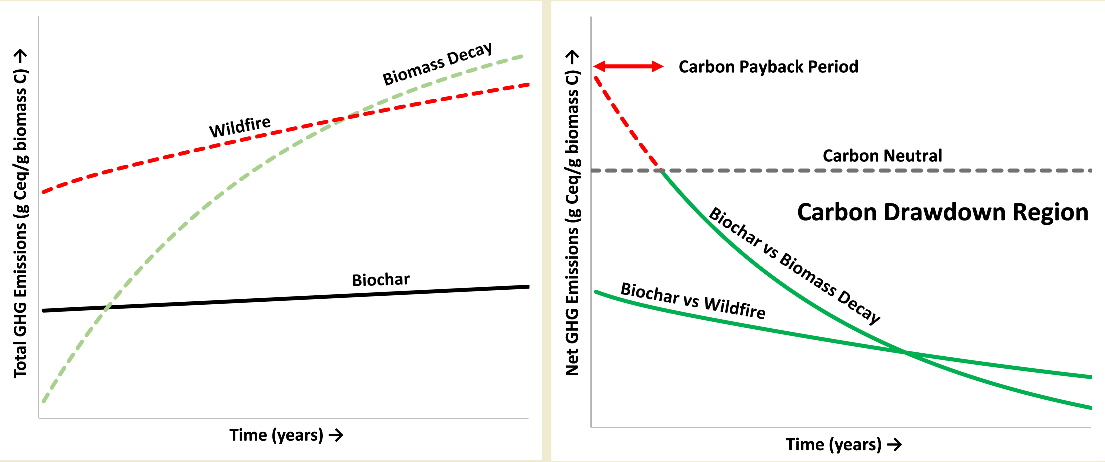


Figure 1. Hypothetical time-sensitive LCA of biochar technology

Two stages in a hypothetical time-sensitive LCA of biochar technology from Amonette et al. 2021.15 (Left) Total GHG emissions of biochar and two alternative fates of the same woody biomass feedstock (decay in place and wildfire). (Right) Net GHG/A emissions of the biochar approach relative to biomass decay and to wildfire. The C-payback period is the period during which biochar technology has higher cumulative GHG emissions than the biomass-decay option.

Beyond decision support and refining LCAs, two specific areas of active scientific research, among many, have the potential to address critical research and implementation gaps. The first is exploring potential synergies among three terrestrial carbon-drawdown technologies (biochar, soil organic matter, enhanced rock weathering). For example, recent evidence[3-6] shows that biochar amendment to sub-humid, temperate-zone soils catalyzes an increase in soil organic matter levels, implying that biochar amendments are synergistic with soil health management systems' ability to draw down carbon. In addition to the direct climate and soil productivity benefits, there are implications for sustainable crop-residue removal rates. Where biochar maintains or increases soil organic matter levels sufficiently, the system may allow for more removal of crop residues for bioenergy/biochar production thereby increasing total carbon drawdown. Another example of synergy is the potential use of the thermal energy and CO_2 generated during biochar production to actively weather rocks containing calcium and magnesium silicates to produce bicarbonate alkalinity and carbonate solids.

The second area of active research involves developing new storage reservoirs for biochar in industrial products such as concrete and asphalt. The potential exists for biochar amendments to make carbon-negative concrete through a combination of improved durability, and displacement of ordinary Portland cement and fine aggregate. Similarly, a cost-competitive asphalt replacement is being tested by a 50-ton-per-day autothermal fast-pyrolysis system in Iowa. These new storage options for biochar may provide the economic incentives to produce more biochar, and thereby help subsidize biochar designed for agricultural uses where cost seems to be a primary hurdle to widespread adoption. There are limits to the amount of biochar that agricultural lands can accept, and thus, in the long run, other storage options will be needed to continue the carbon drawdown process.

Farmer Perspectives

The experiences of foresters, ranchers, and farmers already using biochar can help inform research priorities and smooth the path to broad commercialization. The below highlights are drawn from convening discussions and phone interviews with practitioners involved in biochar production and use. Though practitioners represented diverse farming systems and geographies, similar themes emerged.

Figure 2: Biochar being loaded, applied, and incorporated on an agriculture field.

Steve Charter, a Montana rancher, is incorporating biochar in his vermicompost worm beds, using the co-composted biochar to speed up the restoration of his soil's microbial community. Charter is also incorporating biochar into his cattle feed, adding biochar to his rangeland via manure. His hope is that the dung beetles that populate his grasslands will carry the biochar deeper into the soil. "You can't go out and do a bunch of stuff if the economics don't work – even if it's a good idea", Charter said. Charter highlighted a recurring theme, that providing economical and scientifically proven practices and products will be key to farmer adoption.

Shakera Raygoza owns Terra Preta Farm in Texas, named after the famous "Terra Preta" soil of the Amazon. She hopes to produce biochar in partnership with the city of McAllen, Texas. The city collects brush and compost that could be used as feedstock. For Raygoza, biochar represents another market opportunity as the local municipality is interested in buying her biochar products. She recently applied her biochar to a quarter-acre cucumber plot to improve fertility. Raygoza recently highlighted her efforts at a U.S. House Committee on Agriculture hearing on March 16, 2022.

Dave Atkins is a forest landowner in Montana's Blackfoot Valley. Atkins is producing biochar to thin his 159-acre forest, reduce wildfire hazard, decrease insect and disease risks, reduce irrigation use on his hazelnut orchard, and store carbon. He envisions helping his neighboring tree farms adapt to drier summers and sequester carbon. "The potential is phenomenal," Atkins says. "The barrier is adoption and the uncertainty – we need to accelerate through this phase."

Arthur's Point Farm in New York produces feedstock, processes biochar on-site, and applies a biochar/compost amendment to their orchards, and nursery trees and plants. The farm purchased a retort kiln in 2020 that produces a low-ash, near-neutral pH biochar from wood from the property and local lumber yard scraps. The biochar is blended with on-farm compost and local biological inoculant to create a probiotic biochar soil amendment, which they sell and use. Dave Newman, the farm's Managing Director, emphasizes the importance of site-specific, applied research. The farm has a U.S. Department of Agriculture's (USDA) Sustainable Agriculture Research and Education (SARE) funded project with ten other local farms to evaluate the effects of different biochar/compost amendments on soil health, soil biological communities, soil carbon sequestration, and tree/crop productivity. The operation also actively manages to regenerate the forest that provides their biochar feedstock and recognizes that biochar and forest management are linked with climate mitigation.

Interest in biochar for Harry Stine, the CEO of Stine Seed Company in Iowa, was serendipitous. Stine owns land in Ghana, located next to an area where Dutch settlers had built and operated a charcoal kiln in the 1800s. The refuse from the kiln operation, which was partly biochar, ran down part of Stine's field. Farm operators noticed that the areas that accidentally received "biochar amendments," had twice the yields. Since then, Stine has invested in biochar production. In June 2022, the Stine pyrolysis plant, a collaboration between Stine Seed Farms, Frontline BioEnergy, and Iowa State University, began trials to transform biomass into biochar and bio-oil.

Research and the importance of working with land-grant universities is another universal refrain. Charter stressed a desire to document his research and would like to work with a university research partner. Raygoza collaborates with the University of Texas to develop a new revenue stream while increasing yield. Atkins works with the University of Montana Forestry School, and his operation will be the subject of a graduate research paper. Newman also stressed the importance of practical, applied, on-farm research, especially in perennial production systems. Stine is collaborating with Iowa State University soil scientists.

For all the good ideas, research, and innovation that these farmers, foresters, and ranchers have to offer, the hardest sell may be to their neighbors. “They think I’m crazy,” Charter said. Stine added that while he does not know what his neighbors think of his pyrolysis facility, his neighbors do not adopt his practices and recommendations even when they see his success. Atkins, on the other hand, notes that after he has explained that biochar can sequester carbon for 1,000 years, mitigate drought and extend their irrigation water, his neighbors say, “This is really cool!”

Breakout Group Discussion Summary – Day 1

Day 1: Necessary structures, players, and funding to fill biochar knowledge gaps and meet research needs

Improved knowledge sharing

Consistent messaging of benefits

More site-specific recommendations

Integration of biochar as a tool in the soil health management systems toolbox

Research on commercial applications

Additional discussion around incentives

On-the-ground feedback through farm service training and extension

Improved accessibility of biochar

Improved understanding of the economics of biochar application in agriculture

Standardization and coordination across Federal and Non-Federal activities

Full Discussion Summary available in Appendix 3.

Section 3. Convening Day 2

Pyrolysis Biochar Bioenergy Industry: Agronomic Viability & Sustainability

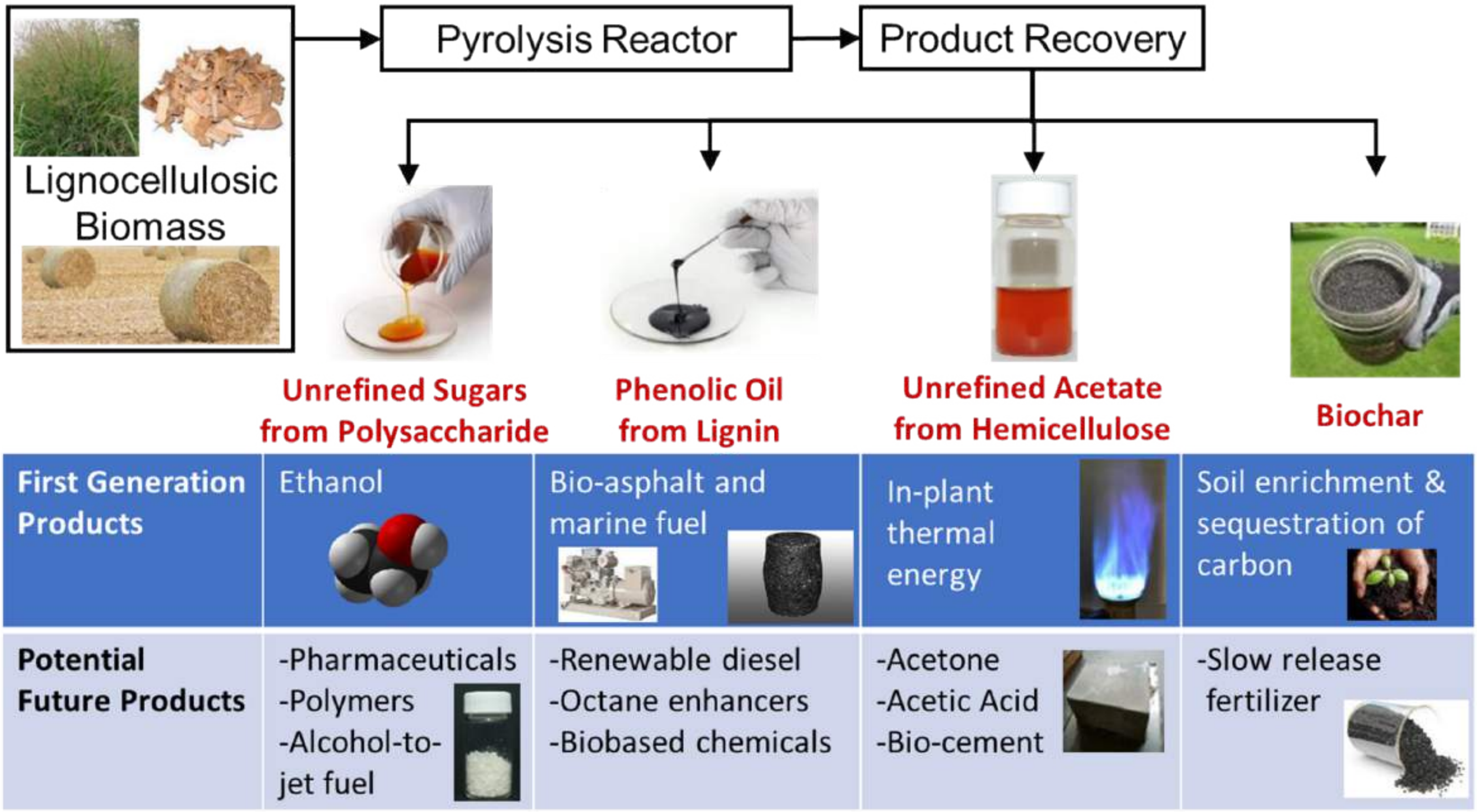
According to Li et al, 2017,[50] the PBBI platform has the potential to produce carbon negative energy products, including diesel, jet, and marine liquid transportation fuels, as well as biochar. The proposed PBBI differs from other proposed bioenergy systems in that biochar is an intrinsic co-product, which can be applied for agronomic benefits.[51]

Soil scientists have raised concerns about the long-term sustainability of many proposed bioenergy systems. The proposed PBBI, in addition to making economical use of agricultural and forestry residues and other low-value organic wastes products, produces biochar and bioenergy for environmental benefits. However, the amount of biomass harvested for bioenergy production is limited by the necessity to sustain soil health.[52] Over time, agricultural soils subject to excessive, poorly managed biomass harvesting will be acidified and mined of plant nutrients and will have reduced aggregation and soil organic matter levels, higher bulk density, lower porosity, and lower water and nutrient holding capacity. However, when biochar is returned to the soils from which the biomass is harvested, there is the potential to maintain nutrient and soil organic matter levels and soil health. Especially when biochar is integrated into production systems along with additional soil health management practices, soil organic matter increases can be additionally maintained or improved indirectly through negative priming, as discussed previously. Hence, with biochar amendments, it is possible to sustainably harvest significant amount of aboveground crop residues on prime agricultural lands. One critical need is to maintain enough soil surface cover to prevent erosion and protect soil health, which can be accomplished through a combination of leaving sufficient residues and/or excellent cover crop or other vegetative cover management for maximized soil cover throughout the crop year.

Sustaining a PBBI also requires addressing the safety challenges of managing biochar as an agricultural soil amendment. When the final biochar product is a fine powder, it can be difficult to safely apply and can even be a fire hazard. However, this problem can be largely mitigated through hydrating the biochar, prilling it with a small amount of binder to form granules, and composting or otherwise combining the material with other amendments. Further, education and training on proper handling and storage, application methods, and Personal Protective Equipment can promote human and environmental safety and minimize hazards.[53]

State & Commercial Readiness of Pyrolysis

Pyrolysis can be conducted under regimes characterized as slow or fast. Slow pyrolysis is distinguished by low heating rates resulting in predominately biochar and gas products. Fast pyrolysis involves both high heating rates of biomass and rapid quenching of vapors to produce primarily liquid products although biochar and gas are also produced. A prominent advantage of slow pyrolysis is the relative simplicity of reactor construction and operation, making them suitable for small facilities processing widely distributed biomass supplies. In addition, slow pyrolysis generally converts a higher proportion of biomass carbon to biochar. Another distinction is that the co-product of slow pyrolysis is a low caloric value gas, while the bio-oil from fast pyrolysis has potential for upgrading to value-added products. Fast pyrolysis is likely more profitable than slow pyrolysis. The economics are less attractive for the production of biochar without bioenergy co-products because farmers are unlikely to pay more than $100 per ton for biochar used as a soil amendment. By producing multiple products, pyrolysis biorefineries are expected to help improve the profitability of pyrolysis, especially as demand for low-carbon fuels increases. Furthermore, biorefineries can be envisioned that fractionate bio-oil into multiple products, as illustrated in Figure 3. As society and corporations continue to become more willing to pay for the removal of carbon dioxide from the atmosphere, the economics of biochar production, as well as its use in agriculture, are expected to further improve.



	Unrefined Sugars from Polysaccharide	Phenolic Oil from Lignin	Unrefined Acetate from Hemicellulose	Biochar
First Generation Products	Ethanol	Bio-asphalt and marine fuel	In-plant thermal energy	Soil enrichment & sequestration of carbon
Potential Future Products	-Pharmaceuticals -Polymers -Alcohol-to-jet fuel	-Renewable diesel -Octane enhancers -Biobased chemicals	-Acetone -Acetic Acid -Bio-cement	-Slow release fertilizer

Figure 3. Concept of a pyrolysis refinery (Source: Iowa State University)

A prominent technical challenge in scaling and commercializing pyrolysis systems is heating the reactors as their size increases – the rate at which heat can be transferred into the reactor grows more slowly than the rate at which biomass can be processed through it. Autothermal pyrolysis, which introduces a small amount of air into the reactor, overcomes this heat transfer bottleneck by partly oxidizing some of the products of pyrolysis, generating thermal energy internally.[54] The result is both the simplification of reactor design and dramatic intensification of the process.

A conceptual model for a sustainable PBBI is presented in Figure 4. The industry is envisioned as a network of relatively small pyrolyzers that process locally obtained waste organic residues and harvested biomass. The biomass feedstock could be crop residues, forest residues (harvested to reduce wildfire risk), orchard trimmings, or purpose-grown bioenergy crops such as miscanthus, switchgrass, or coppiced willows. The bioenergy co-products are either sold directly to end users (bunker fuel or bioasphalt) or shipped to a refinery for upgrading to higher value products such as polymers and jet and diesel fuels. The biochar co-product is returned to the lands from which the biomass was harvested, or to those local soils that are most degraded and positively responsive to biochar amendments. The amount of biogenic carbon in harvested biomass that can be sequestered via pyrolysis ranges from 10 to 55%.[55] Secondary biochar effects such as enhanced crop productivity, negative priming, and reduced need for fertilizer would further offset GHG emissions.

Opportunities & Challenges: Commercialization of the Pyrolysis Biochar Bioenergy Industry

There is significant evidence that biochar and pyrolysis can sequester carbon, enhance agricultural productivity, and promote energy independence.[56] However, these technologies are still evolving, and publicly supported research and experimentation are essential to pushing the technology forward. Public-sector investment is critical during the early, high-risk stage of new industries; for example, public-sector investment greatly accelerated the growth of wind and solar energy industries. Meaningful implementation requires the involvement of the private-sector and especially the energy and other offtake sectors. One common thread throughout the convening was that this meaningful implementation can only occur with a coordinated strategy from both the public and private sector.

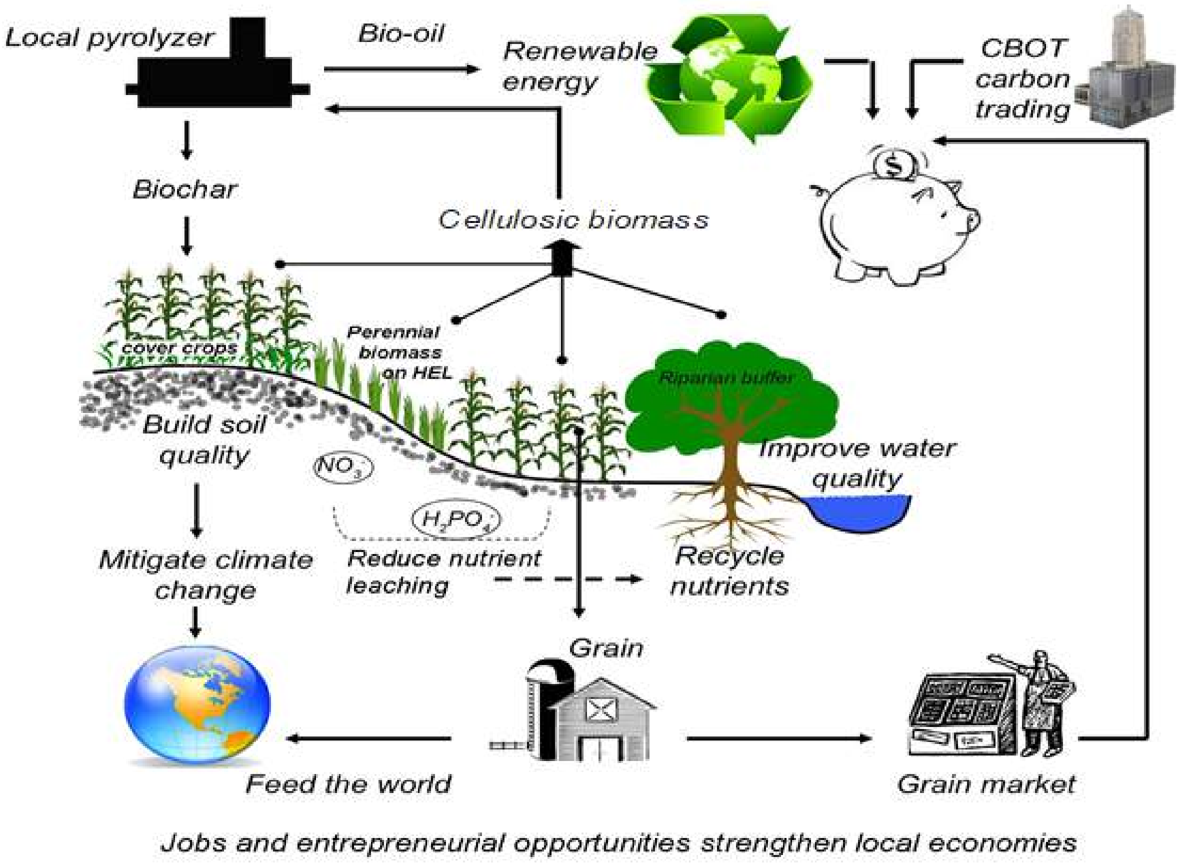


Figure 4: Conceptual model for a sustainable Pyrolyisis Biochar Bioenergy Industry

Oil companies have realized that their long-term investments in hydrocarbons are at risk. As such, some are considering transition strategies and decarbonization, depending on their reserve, discovery capacity, and corporate strategies. Other companies are interested in alternative fuels sources. Companies with large oil reserves may be more committed to fossil fuels, while others with large amounts of natural gas have more interest in developing blue hydrogen. Companies' strategies depend on their resources. Almost all companies would like to offset GHG emissions from the transportation sector, which has been difficult to decarbonize. An investment in a PBBI can support a broad decarbonization strategy. However, supportive policies are necessary across all sectors.

An investment in a PBBI can support a broad decarbonization strategy.

Policy makers speak about decarbonization as a long-term goal but are often diverted by short-term economic and political pressures. The low carbon fuel standard is a good example that encourages decarbonization. The proposed U.S. carbon capture credit is very promising. There is potential for the EU's carbon trading mechanism to expand to fuels as well. Strong policy support for biochar would facilitate decarbonization, improve soil health, and help control wildfires where woody residues are abundant. Industry will support initiatives that will become profitable and research that will enhance commercialization. With more supportive policies, we expect new players to emerge. The big challenge is to identify opportunities for biochar while the industry is being developed. We need to identify areas of the country with sustainable, available, and low-cost feedstocks, opportunities for biochar applications, and high value from decarbonization.

The economic viability of PBBI is also closely tied to the price of petroleum and associated regulations, taxes, or carbon credits, as biofuels directly compete with petroleum. The agronomic value of biochar amendments is relatively low except where significant increases in crop yield are produced, such as on degraded, acidic, coarse textured soils. **Hence, it is critical that 1) the cost of biochar be minimal, 2) that farmers receive carbon credit payments for biochar applications, and 3) that highly usable decision support tools be available for targeting biochar applications as discussed above.**

Breakout Group Discussion Summary – Day 2

Day 2: What is needed to move biochar technology and its commercialization forward?

Efficiency in production and lack of widespread availability of biochar is currently holding the market back

Scale

Community-based smaller scale biochar production facilities represent a huge opportunity

There is a lot of federal funding in the space right now, and many potential synergies that can be aligned by working with local and regional groups.

Full Discussion Summary available in Appendix 3.

Section 4. Conclusions

The convening on biochar research and commercialization, co-hosted by FFAR, NCAT, and AFT brought together experts to discuss the sustainable production and use of biochar as a critical tool in the soil health and climate-smart toolbox. Convening participants identified the need for current actionable, coordinated, large-scale research relevant to commercial production in the next five years to address key gaps: improving soil productivity, management decision support, and LCA and quantification of climate mitigation potential. Research gaps were also identified in potential synergies among biochar, soil organic matter, and enhanced rock weathering and in development of new storage reservoirs for biochar in industrial products. Scaling up a PBBI urgently requires a coordinated, multi-faceted strategy among conservationists, farmers and ranchers, researchers, industry, and policy experts to address agronomic, environmental, human, economic, technology, and production concerns.

The convening resulted in overarching recommendations to support the rapid development and leveraged integration into soil health and climate-smart systems transitions of a PBBI that facilitates the application of sustainable, fit-for-purpose biochars to increase soil health and mitigate climate change. NCAT and AFT are developing a companion white paper to outline recommendations for scaling up sustainable biochar production and use that will be published in early 2023.

Appendices

Appendix 1: Convening Agenda

Agenda Day 1 (Zoom recording available here)

Welcome and Charge

12:00 pm	**Welcome + Housekeeping** Ryan Neal (Zoom) and LaKisha Odom (FFAR) **Welcome and Context + ARS Collaboration** Marlen Eve, Agricultural Research Service (ARS) **Co-Sponsor Comments** Bianca Moebius-Clune, American Farmland Trust (AFT) Steve Thompson, National Center for Appropriate Technology (NCAT) **Introduction to FFAR & Meeting Objectives** LaKisha Odom, FFAR

Research Strategy for Addressing Knowledge Gaps on Biochar

12:40 pm	**Brief Introduction of Speakers** Chuck Hassebrook, Biochar Policy Project, National Center for Appropriate Technology (NCAT) Speaker bios available at the Farmland Information Center
12:45 pm	**Integrated Biochar Research: A Roadmap** Jim Amonette, DOE Pacific Northwest National Laboratory and Washington State University
1:05pm	**Biochar Research at Agricultural Research Service and Fit Within Research Roadmap** Kristin Trippe, ARS Biochar Research Leader
1:20 pm	**Forest Service Research on Biochar in Forest Soils and Fit Within Research Roadmap** Carlos Rodriguez-Franco, Senior Leader for Strategic Forest Science Synthesis, USDA Forest Service
1:30 pm	**Research Infrastructure to Implement the Roadmap and Fill the Knowledge Gaps on Biochar** Johannes Lehmann, Liberty Hyde Bailey professor of soil and crop sciences, School of Integrative Plant Science, Cornell University

1:40 pm	**Farm Perspective on Biochar Research** Bruce Rohwer, Paullina Iowa farmer and member of the board, National Corn Growers Association
1:50 pm	**Time for Questions of Clarification to the Presenters**
2:00 pm	**10-minute Break**
2:10 pm	**Charge to Small Group Discussions** Chuck Hassebrook, NCAT
1:20 pm	**Small Group Research Strategy Discussion** Small groups focused on structure, players and funding to fill biochar knowledge gaps and meet research needs. • What is most needed to enable farmers, ranchers, foresters and other land-managers to ramp-up application of biochar? • Is the Research Roadmap presented by Jim Amonette the right framework for filling the critical knowledge gaps on biochar? What additions or refinements are needed? • For which applications is current knowledge of biochar sufficient to encourage its adoption now and how can the experiences of farmers, ranchers and foresters using it inform research? • What are the most critical steps research agencies and institutions can take now to advance biochar research?
3:15 pm	**Return to Full Group for Reports Back and Full Group Discussion**
3:55 pm	**Wrap-Up for Day 1**
4:00 pm	**Adjourn for Day 1**

Agenda Day 2 (Zoom recording available here)

Policy and Investments to Develop a Pyrolysis-Based Biochar and Biofuel Industry

12:00 pm	**Day 2 Kickoff** LaKisha Odom, FFAR **Reflections on Day 1** Bianca Moebius-Clune, American Farmland Trust (AFT)

12:10 pm

Brief Introduction of SpeakersPyrolysis Biochar Bioenergy Industry: Agronomic Viability & Sustainability

David Laird, President & CEO N-Sense Inc. & Professor Emeritus Soil Science Iowa State University

Speaker bios available at the Farmland Information Center

12:30 pm

State and Commercial Readiness of Pyrolysis Technology

Robert Brown, Iowa State University

12:50 pm

Opportunities and Challenges to Commercialization of the Pyrolysis Biochar Bioenergy Industry

David Zilberman, Robinson Chair and Professor, Agricultural and Resource Economics Department University of California, Berkeley

1:05 pm

Boeing and Commercial Aviation Industry Perspectives on Sustainable Aviation Fuels (SAF)

Dale Smith, Director, Enterprise Environmental Sustainability, The Boeing Company

1:20 pm

DOE Strategy for Developing and Commercializing Low Carbon Aviation and Shipping Biofuels and Potential Role for Fuels Co-Produced With Biochar

Nichole Fitzgerald, DOE Bioenergy Technologies Office

1:30 pm

Time for Questions of Clarification to the Presenters

1:40 pm

10-minute Break

1:50 pm

Charge to Small Group Discussions

David Laird, N-Sense Inc. & Iowa State University

1:55 pm

Small Group Discussion: What is Need to Commercialize Fuels Co-Produced with Biochar?

Small groups focused on what is needed to move the technology and its commercialization forward.

- What are the critical technology hurdles that must be overcome before the pyrolysis biochar bioenergy industry will be ready for commercialization?
- What are the critical policy hurdles to commercialization of the pyrolysis biochar bioenergy industry?
- What can DOE and USDA do to promote commercialization of the pyrolysis biochar bioenergy industry?
- What will incentivize private industry to invest in commercial development of the pyrolysis biochar bioenergy industry?

	- Do presentations or discussion today change any conclusions we reached yesterday?
3:00 pm	**Reports Back and Discussion**
3:45 pm	**Next Steps and Closing**
4:00 pm	**Adjourn**

Appendix 2: More Information about the Convening Organizers

About the Foundation for Food & Agriculture Research (FFAR)

The Foundation for Food & Agriculture Research (FFAR) builds public-private partnerships to fund bold research addressing big food and agriculture challenges. FFAR was established in the 2014 Farm Bill to increase public agriculture research investments, fill knowledge gaps and complement USDA's research agenda. FFAR's model matches federal funding from Congress with private funding, delivering a powerful return on taxpayer investment. Through collaboration and partnerships, FFAR advances actionable science benefiting farmers, consumers and the environment.

Specifically, FFAR's Soil Health Challenge Area seeks to advance biochar research to reduce emissions, harness the soil health benefits and implement and scale biochar adoption. FFAR aims to coordinate funding opportunities to support near-term technology development for biochar.

About the National Center for Appropriate Technology (NCAT)

The National Center for Appropriate Technology has been helping people build resilient communities through local and sustainable solutions that reduce poverty, strengthen self-reliance, and protect natural resources since 1976. We do this through a trusted knowledgebase, providing individualized technical assistance, facilitating practical solutions, and connecting people with each other to support sustainable agriculture and clean energy systems. NCAT's ATTRA Sustainable Agriculture specialists, located in 10 states, assist farmers with climate solutions that help them adapt to climate disruptions while reducing carbon emissions. The Soil for Water program connects agricultural producers seeking to make their farms and ranches more resilient through regenerative practices in the face of persistent drought and other natural disasters. NCAT promotes the regionally appropriate production and utilization of biochar as an important element of the climate solutions toolkit.

About American Farmland Trust (AFT)

American Farmland Trust is the only national organization that takes a holistic approach to agriculture, focusing on the land itself, the agricultural practices used on that land, and the farmers and ranchers who do the work. AFT launched the conservation agriculture movement and continues to raise public awareness through our No Farms No Food message. Since our founding in 1980, AFT has helped permanently protect over 6.8 million acres of agricultural lands, advanced environmentally-sound farming practices on millions of additional acres and supported thousands of farm families. AFT is committed to making U.S. agriculture a critical part of the climate solution. To do so, we are elevating the role of farmers, ranchers, and the land they manage in adapting to and mitigating the effects of climate change. From policy leadership, coalition building, and training to research and on-the-ground demonstration projects, we are working to scale up the adoption of diverse regenerative and soil health promoting agricultural systems. AFT is promoting the use of sustainably produced and applied biochar as a tool in the soil health management toolbox that improves soil function, increases adaptation and resilience, and mitigates climate change.

Appendix 3: Full Breakout Discussion Summary

For each day of the convening, attendees were asked to provide insights on two key topic areas:

- What are the structures, players and funding necessary to fill biochar knowledge gaps and meet research needs?
- What is needed to move biochar technology and its commercialization forward?

Necessary structures, players and funding necessary to fill biochar knowledge gaps and meet research needs (Day 1)

Improved Knowledge Sharing: A common theme in all the breakout groups was the need for more knowledge sharing between all stakeholders involved.

- There was consistent agreement that there is a need for more on-farm demonstration trials and more farmer-to-farmer knowledge exchange to illustrate the localized potential.

Consistent messaging of benefits: Even among biochar researchers, the messaging regarding benefits is inconsistent because biochar may have different impacts in various environments based on factors ranging from biochar type to soil type to regional climate.

- There was discussion of a need to provide messaging to manage farmer expectations of the benefits of biochar.
    - It is imperative that there is a more complete understanding of the economics of integrating biochar into an existing management system from the farmers' perspective. The financial benefits may not be there within the first few years, but there is a strong connection between biochar and healthy soils, ecosystem services, etc.

More Site-Specific Recommendations: There is so much variation in soil and biochar types that site-specific recommendations are necessary. Without tailored information based on location, the results of adoption may be misleading or disappointing to both farmers and researchers. Without ensuring farmers identify the right biochar for their respective soil type, there will be wasted carbon capture potential.

Integration of biochar as a tool in the soil health management systems toolbox: Farmers manage systems and are increasingly aware of the benefits of cover crops, diversification of production systems through crop rotation and livestock integration, reduced tillage, and other practices. Biochar research must be integrated in on-farm and long-term research trials as a tool in the systems toolbox for developed recommendations for effective adoption to be able to leverage and build on the momentum of soil health transitions.

Research on commercial applications: Throughout the first discussion day, there was mention of need for parallel research on commercial applications

Additional discussion around incentives: Not just financial incentives, but also incentives for soil health and farm productivity.

On-the-ground feedback through farm service training and extension: Knowledge and technology need to be more locally available, and increased outreach and education can increase this information transfer.

Improved accessibility of biochar: There is a strong need to connect local manufacturers of biochar systems with local end users, because many smaller producers simply do not have access to the biochar production volume they need at a price point they can afford.

Improved understanding of economics: Short-term economic cost and yield needs to be balanced with the potential for long term benefits related to soil health and ecosystem services.

Standardization and coordination across federal and nonfederal spaces: The breakout groups discussed many ways to standardize and coordinate across federal spaces, industry, and academia.

- Connections are needed beyond single agencies, and beyond the federal space into the non-profit realm. Funders are aware that there is a wealth of research happening at USDA on biochar and would find it valuable to have one place to see what is being done within the agency to better understand what additional gaps are not being addressed. Currently, there is no central resource with this information.
- There is a need for much more inter-agency collaboration and support of the biochar space.
- In addition to immediate federal interest in biochar, there is a continued need for long term funding opportunities because the impacts of adoption can take years to come to fruition, and regional tailoring is necessary to unlock biochar's true potential. There are various entry points across all levels of stakeholder engagement that should be embraced both locally and nationally.
- The need for more citizen science outreach and extension programs was stressed, as well as the incorporation of biochar at the long-term agricultural research sites around the country.
- Many felt that it was important to integrate research at the local and state levels, as well as incorporate biochar into regenerative agriculture efforts, as opposed to thinking of biochar as a separate piece of the puzzle. There is a strong need for consistency and assimilation of biochar into the larger regenerative agriculture conversation.

What is needed to move biochar technology and its commercialization forward? (Day 2)

Efficiency in production and lack of widespread availability of biochar is currently holding the market back.

- Currently, there is more biochar production than there is biochar adoption, and often the producers of high-value crops are the only adopters who can afford the upfront cost.
- Additional research is needed on the potential for profit and increase of soil fertility and carbon sequestration. Multiple groups talked about carbon credits and how they have a large potential to make biochar economically viable for most production agricultural systems.

- Given the often low agronomic value of biochar applications, carbon credit payments need to be structured so that farmers and landowners receive sufficient compensation to cover their costs and are incentivized to apply biochar on their land.
- Some breakout groups asserted that biochar commercialization is technically doable already, but the lack of markets and specifications is preventing widespread adoption. Others countered that mismatched time expectations from various stakeholders are holding back further industry development
    - Bioenergy advancements, carbon fuel standards, and sustainable aviation fuels all fit within a potential market for biochar and could serve as a non-primary driver of technology growth and scaling up.
- It was suggested to connect feedstock suppliers with bioenergy technology companies and encourage the suppliers to invest in the technologies instead of the biomass itself. This would keep suppliers in the loop as stakeholders and ensure that everyone involved is receiving the benefits

Scale: The breakout groups spent much of the discussion focused on how to transition from what's been proven in the lab to deploying it at scale in the field.

Community-based smaller scale biochar production facilities represent a huge opportunity; there is a lot of federal funding in the space right now, and many potential synergies that can be aligned by working with local and regional groups.

- One specific suggestion for federal investment focused on the need for more rapid testing and on-site analysis, and the potential for mobile technology development with local pilot testing of these tools in the field. The importance of local policy and site-specific education came up multiple times throughout both days of the event, as well as the need for federal and local coordination on the value of biochar.

The throughline in each of the breakout group discussions over the two-day event centered around the need for both local and national solutions, the need for improved and consistent information sharing and messaging, the need for more coordination across federal and nonfederal spaces and the existing areas of potential to develop a market for biochar within existing frameworks.

Appendix 4: Acknowledgements and Disclaimer

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