Biomass *to* Biochar

Maximizing the Carbon Value

JANUARY 2022 (v1.1)

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COVER PHOTO ATTRIBUTION

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LIST OF ABBREVIATIONS

The following abbreviations are used throughout this document. Please refer to this table where definitions are not provided following the term in the text.

Abbreviation	Definition
AAPFCO	Association of American Plant Food Control Officials
ACI	air curtain incinerators
ARS	USDA Agricultural Research Service
ATC	Authority to Construct
BACT	Best Available Control Technology
BD	bone dry
BRDI	Biomass Research and Development Initiative
BPS	biochar production systems
BUC	Biomass Utilization Campus
C	carbon
CAGR	compound annual growth rate
CARB	California Air Resources Board
CDFA	California Department of Food and Agriculture
CEC	cation exchange capacity
CEQA	California Environmental Quality Act
CFLRP	USDA USFS Collaborative Forest Landscape Restoration Program
CGIAR	Consortium of International Agricultural Research Centers
CH_4	methane
CHAB	combined heat and biochar
CISWI	Commercial and Industrial Solid Waste Incineration Units
Cl_2	chlorine gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
$CO_2e\ T^{-1}$	carbon dioxide equivalent per ton
CY	cubic yard
DMDS	dimethyl disulfide
EBC	European Biochar Certificate
EBBCD	Endowment for Biochar-Based Community Development
EPA	U.S. Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-to-Know Act of 1986
EQIP	Environmental Quality Incentives Program
ERC	Emissions Reduction Credits
EU	European Union
FDA	U.S. Food and Drug Administration
GHG	greenhouse gas
GRACEnet	Greenhouse gas Reduction through Agricultural Carbon Enhancement network
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
Gt	gigatonne or billion metric tonnes
GT	gigaton or billion U.S. tons
GWP_{100}	global warming potential
ha	hectare
HAP	hazardous air pollutants
HCl	hydrogen chloride
HPLC	high performance liquid chromatography
HRA	health risk assessment
IBI	International Biochar Initiative
IPCC	Intergovernmental Panel on Climate Change
$KMnO_4$	potassium permanganate
LCA	life cycle assessment
LCFS	Low Carbon Fuel Standards
LTBR	long term biochar research

MMBtu	1 million BTU British Thermal Unit.
MSW	municipal solid waste
Mt	megatonne or million metric tonnes
MT	megaton or million U.S. tons
MW	megawatt (can refer to energy content of biomass going into the plant as well as energy output by the plant)
MWe	megawatt of electrical output (by an energy plant)
NAAQS	National Ambient Air Quality Standards
NEPA	National Environmental Policy Act
NGO	non-governmental organization
NH_3	ammonia
N_2O	nitrous oxide
NO	nitric oxide
NO_2	nitrogen dioxide
NO_3^-	nitrate
NOx	generic term for the nitrogen oxides that are most relevant for air pollution, namely nitric oxide and nitrogen dioxide
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Laboratory
NSR	New Source Review
NWFP	Northwest Forest Plan
O_3	ozone
ODEQ	Oregon Department of Environmental Quality
ODT	oven dry ton
OFRI	Oregon Forest Resources Institute
OMRI	Organics Materials Review Institute
OSWI	Other Solid Waste Incinerators
PAH	polycyclic aromatic hydrocarbons
Pb	lead
PM	particulate matter
$PM_{2.5}$	particulate matter with a diameter 2.5 micrometers or smaller
PM_{10}	particulate matter with a diameter of 10 micrometers or smaller
PNW	Pacific Northwest
ppbv	parts per billion by volume
PSD	Prevention of Significant Deterioration
PTO	Permit to Operate
RCPP	Regional Conservation Partnership Program
RFRS	Remote Forest Research Stations
ROG	reactive organic gases
SEPA	State Environmental Policy Act
SO_2	sulfur dioxide
TPY	tons per year
USBI	United States Biochar Initiative
USDA	United States Department of Agriculture
USFS	United States Forest Service
VOC	volatile organic compounds
wt. %	percent by weight

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Executive Summary

James. E. Amonette, James G. Archuleta, Mark R. Fuchs, Karen M. Hills, Georgine G. Yorgey, Gloria Flora, Josiah Hunt, Han-Sup Han, B. Thomas Jobson, Tom R. Miles, Deborah S. Page-Dumroese, Sean Thompson, Kelpie Wilson, Raymond Baltar, Ken Carloni, Douglas P. Collins, James Dooley, David Drinkard, Manuel Garcia-Pérez, Kai Hoffman-Krull, Marcus Kauffman, David A. Laird, Wayne Lei, John Miedema, John O'Donnell, Adrian Kiser, Brennan Pecha, Carlos Rodriguez-Franco, Grant E. Scheve, Carson Sprenger, Bruce Springsteen, and Edward Wheeler

> ***Forty biochar producers, practitioners, scientists, and engineers held a virtual workshop to chart a roadmap for future development of biochar technology in the Pacific Northwest and beyond.***

Converting biomass to biochar (Figure ES-1) presents exciting opportunities to mitigate climate change, improve forest and soil health, decrease wildfire risk, bolster ecosystem services, and revitalize rural economies. Our expert panel examined how biomass is harvested, converted to biochar and applied and where operational changes and funding could significantly magnify biochar's contributions. To advance knowledge and efficacies, we found that a rigorous combination of *long-term multi-site coordinated research, near-term market-focused research and development* and enhancement of *business support infrastructure* that leads to *collaborative policy development* is essential. We also identified how barriers to five specific biochar technology sectors could be overcome and provide guidelines for effective funding.

Figure ES-1. *Biochar production offers a unique opportunity to address pressing environmental and societal issues.(Photo: Simon Dooley, CC BY-NC 2.0)*

BACKGROUND

The Pacific Northwest region of the U.S. is fertile ground for advancement of biochar production and use. Strong industrial and academic expertise, engagement from governmental and non-governmental organizations (NGOs), abundant forestry feedstocks, and diverse agricultural production systems position the Pacific Northwest to realize the potential of biochar. In the process, the region could address four pressing environmental and societal issues including climate change; poor forest health and increasing wildfire risk; air, soil, and water quality; and the decline of rural communities.

The effects of climate change are experienced both regionally and globally, making mitigation imperative. Biochar shows significant promise as one of a suite of climate-change mitigation strategies and offers the possibility of near-term, widespread deployment. Soils have significant capacity to store carbon (C); amending soils with biochar can greatly enhance this potential. Life cycle analyses (LCAs) indicate that biochar offsets greenhouse gas (GHG) emissions by about 0.4-1.2 tons of carbon dioxide equivalents per ton ($CO_2e\ T^{-1}$) of dry feedstock. The amount of sustainably procured feedstock (typically waste biomass from forestry and agriculture) and the efficiency with which the C in it is converted to biochar, will ultimately determine the climate offset potential that is realized. A current estimate[1],

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[1] *Amonette, J.E. 2021. Technical Potential for CO_2 Drawdown using Biochar in Washington State. Report for The Waste to Fuels Technology partnership 2019-2021 biennium: Advancing organics management in Washington State. Center for Sustaining Agriculture & Natural Resources, Washington State University, Pullman, WA. https://csanr.wsu.edu/publications/technical-potential-for-CO2-drawdown-using-biochar-in-washington-state/*

which assumes maximum C-conversion efficiency, suggests that biochar production could annually offset between 8% and 19% of all greenhouse gas emissions in Washington State (taken at 2018 levels)[2].

Decades of fire suppression and changes in forest management have resulted in heavily stocked forests in the Western U.S., while climate change has also increased the risk of high temperature wildfires. Treatments aimed at reducing wildfire risk and improving forest health create large quantities of low value biomass, in addition to those created by logging. These materials are typically gathered in slash piles (Figure ES-2) and burned, resulting in emissions and scars on the landscape where invasive species often take hold. Production of biochar with these forest residues would benefit air quality, improve forest health, and improve the economic feasibility of restoration and hazard fuel reduction work. The biochar could be used onsite to improve forest soils impacted by harvesting and wildfire to increase nutrient retention, mitigate erosion, or address other revegetation challenges. It could also be exported for use in agricultural soils, mined-land reclamation, construction materials, or other purposes.

Beyond forestry, land degradation has occurred on over a quarter of Earth's ice-free land. Biochar—with its high porosity, considerable surface area, and large capacity to retain water, nutrients and contaminants—can be used to avoid, reduce, and reverse degradation of agricultural, rangeland, and forest soils as well as abandoned mines and other severely degraded areas. Biochar's characteristics can enhance water- and nutrient-holding capacities of soil and improve the soil's physical conditions and productivity. Biochar application has been studied most extensively in agricultural soils (Figure ES-3), the magnitude of which provide the potential for moving great quantities of biochar to market. Innovative farmers in the West and beyond are interested in using this amendment to improve soil health and boost crop yields if economic pathways can be demonstrated.

Many rural communities in the Pacific Northwest that had historically relied upon forest-based industries have experienced economic hardship due to the widespread closure of lumber and paper mills from the 1990s to present. Biochar production at various scales could provide a durable engine of economic development in these hard-hit communities.

Realizing these environmental and societal benefits will require that revenues can be generated from the multiple goods and services provided by biochar. These products include thermal energy, soil amendments, stormwater remediation, forest restoration, fire-hazard reduction, and CO_2 removal from the atmosphere. In particular, monetizing CO_2 removal through carbon markets has the potential to make biochar production systems profitable and biochar available at prices that are low enough to support widespread use across a variety of sectors.

Economic viability, while necessary, must be accompanied by other measures of sustainability if the full promise of biochar technology is to be met. These measures include careful consideration of feedstock choices and land use, worker safety, transportation, modes of application, C-conversion efficiency, GHG emissions, stability of C in soil, impact on native

Figure ES-2. *Forest residues piled for burning near Humboldt, California. Burning slash is common in timber harvesting because it's often not economically feasible to collect/process/deliver to a local biomass energy facility.(Photo: Han-Sup Han)*

Figure ES-3. *Researchers Kristin Trippe and Tom Wanzek apply biochar to rangeland soils in Mitchell, Oregon. (Photo: Marcus Kauffman)*

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[2] *A-ECY. 2021.* Washington State Greenhouse Gas Emissions Inventory: 1990-2018. https://apps.ecology.wa.gov/publications/SummaryPages/2002020.html *Accessed 24 September 2021.*

soil-C stocks, and energy use and output. Implementation of this integrated approach over the full life cycle of biochar technology maximizes benefits, minimizes unintended consequences, and ensures success.

WORKSHOP OBJECTIVES

To advance biochar systems in the Pacific Northwest and beyond, 40 biochar practitioners and researchers representing industry, academia, non-profit, and government sectors convened virtually over several months starting in April 2020 with the following objectives:

1. Explore five of the most promising contexts for biochar production and use in the Pacific Northwest, identifying current barriers and the most impactful strategies for moving each sector forward, and
2. Define strategic priorities for investors, philanthropists, policy makers and others looking to help transform biochar technology into a widespread, effective method for addressing climate change while maximizing its beneficial impacts on managed ecosystems and rural communities.

KEY CHALLENGES AND OPPORTUNITIES

We identified a number of key challenges that currently constrain widespread adoption of biochar technologies—and some important associated opportunities. These include:

Technical challenges. Engineering challenges include the need to develop technologies that integrate biomass harvest and handling with biochar production and application, manufacture value-added products, and optimize capture and use of bioenergy. Economic viability, a critical piece of the puzzle, can be achieved through engineering strategies aimed at lowering cost of production and enhancing market value. Scientific challenges include filling critical knowledge gaps in understanding of the global impacts of widespread adoption of biochar technology and of the local impacts of biochar application on soil-plant systems. There is a great opportunity to improve mechanistic understanding of interactions between plants, soil, climate, and the wide variety of biochar types from varying feedstocks and production processes (Figure ES-4). Improved understanding of these interactions would be an important step in development of robust modeling capabilities to predict plant responses and climate impacts and could inform ongoing efforts to produce specialized biochars targeted at specific end uses (e.g., co-composting, mine reclamation).

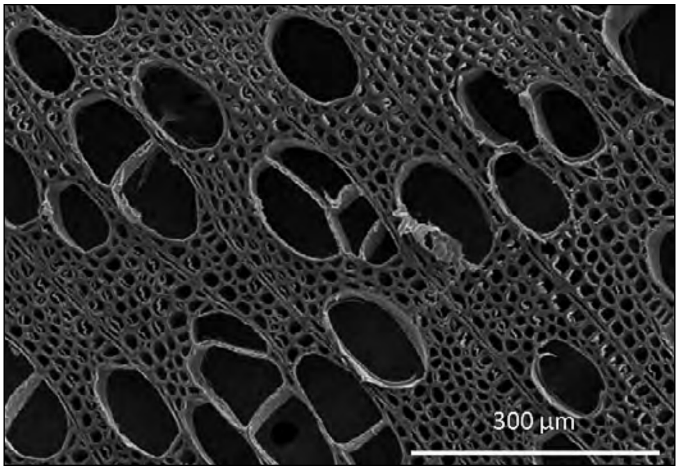

Figure ES-4. *Micropores in biochar vary based on feedstock type and pyrolysis temperature. Shown are electron microscopy images of biochar made from hybrid poplar. Reprinted from Biomass and Bioenergy, Vol 84, Suliman et al., Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. Pages 37-48., Copyright 2016, with permission from Elsevier.*

Economic challenges. Biochar producers face a variety of economic challenges including high costs of production coupled with low market returns, challenges achieving consistent product quality, and a lack of entrepreneurial assistance and financial instruments tailored to the industry. Current economic opportunities exist in niche markets, such as the horticulture industry, but mass-market opportunities are limited by the high production costs. Current air-quality regulations allow open burning of biomass while applying stricter, more expensive rules to cleaner pyrolysis-based production approaches. Biochar production systems are typically classified as incinerators rather than carbon stabilizers. Changing this situation requires dialog with and education of regulatory agencies, coupled with adaption by biochar producers. In a similar vein, concerns about low C-conversion efficiencies and emissions of methane and soot by some biochar production methods offer an opportunity for the industry to adopt more climate-friendly production approaches that do not rely on emission reductions from post-production applications of biochar (e.g., co-composting) to attain carbon-negative status.

Public engagement and support challenges. Engagement with those directly involved in biochar production is critical for advancement of the biochar industry. Currently there is a perceived lack of a central clearinghouse for biochar-related information for those directly involved in biochar systems. Scant specifications or guidance on biomass harvest or handling exist, including workforce training programs or safety protocols for biochar practitioners. Likewise, there are no well-developed biochar outreach and education networks. Forestry contractors have no access to business-planning templates and cost-estimation tools for including biochar in their offerings. General engagement with the public, both to educate potential consumers and to learn of their specific needs, is also needed to help the biochar industry grow.

More detail on these technical, economic, and policy challenges and opportunities is presented in Chapter 2.

RECOMMENDED FUNDING STRATEGIES

To address the challenges and capitalize on the opportunities we recommended strategic investment in four broad areas: 1) long-term research to develop understanding of key processes, 2) near-term research focused on market-development activities, 3) improvement of the infrastructure to support business development, and 4) collaborative development of policy based on engagement with industry stakeholders and the general public (Figure ES-5).

The first of these strategic funding areas provides the foundational science and engineering that support the other three areas, which focus on building a biochar industry. Insights from progress in one area help inform the direction of the others, as does active engagement with stakeholders and the general public. Many different types of organizations will have a role to play in helping biochar technology reach its potential, including philanthropic organizations, local, state, and federal governmental agencies, and private capital.

Long-Term Coordinated Research Program. A long-term (decade-scale) coordinated research program focusing on engineering, biophysical processes, and development of process-based modeling capabilities has the most promise for efficiently addressing engineering challenges and knowledge gaps relating to biochar production and use (Figure ES-6). Such an effort could also play an important role in knowledge consolidation and extension by acting as a clearinghouse and connector of the many individuals working on biochar issues throughout the U.S. and beyond. Program direction would include significant input from an advisory council composed of stakeholder representatives.

Priority areas in *engineering* will be focused on lowering the cost of biochar by improving the efficiency of 1) biomass harvest and handling, 2) biochar production, handling, and post-production processing, 3) capture and utilization of bioenergy generated during biochar production, and 4) biochar application. To improve the climate impact of biochar production, work will be aimed at increasing C-conversion efficiency (the fraction of biomass carbon that ends up in the biochar) and decreasing the amount of methane and soot released to the atmosphere during production.

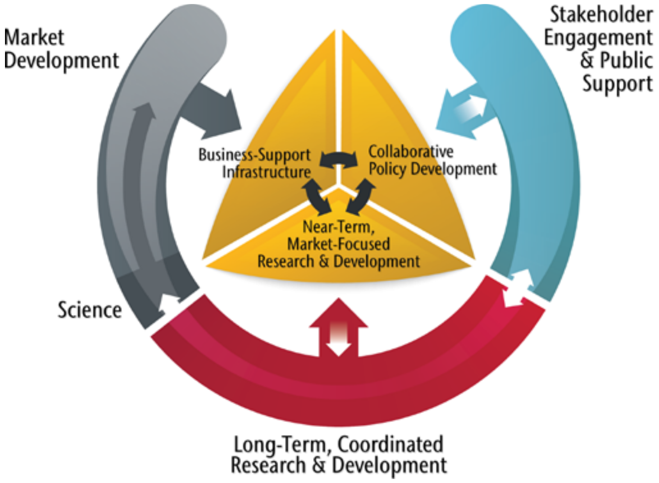

Figure ES-5. *Conceptual diagram of the relationships between the four major priority funding areas recommended by the workshop. Long-term coordinated research & development (in red) provides the foundational science and engineering needed to support development of biochar technology. Three closely related areas, shown in yellow, focus on different activities needed to develop markets for a sustainable biochar-based industry. The grey arc on the left shows the transition in focus of the proposed work from foundational science and engineering to market development. The blue arc on the right shows the level of stakeholder engagement and public support required for the proposed work to succeed. (Figure: Andrew Mack)*

Research on *biophysical processes* will increase the understanding of the various climate-related and economic impacts that biochar has when applied to agronomic, horticultural, silvicultural, and grassland systems—as well as its potential role in compost and manure management. Potential impacts to be investigated include changes in crop/biomass production levels, native soil-carbon stocks, greenhouse gas fluxes, compost-production efficiency, fertilizer- and herbicide-use efficiency, and resilience of natural ecosystems.

Predictive computer-based models are essential tools for consolidating knowledge in a form that can be used to solve problems. The fundamental knowledge generated through the long-term coordinated research program would inform *model development* in six major areas including biochar reactor design; logistical optimization of biomass harvest, biochar production, and biochar application networks; plant responses to soil amendments with biochar; life-cycle assessments of net climate impact; techno-economic pathways and macro-economic scenarios for adoption of biochar technology; and integration of productivity responses, life cycle, and economic assessments into general circulation models that predict climate change.

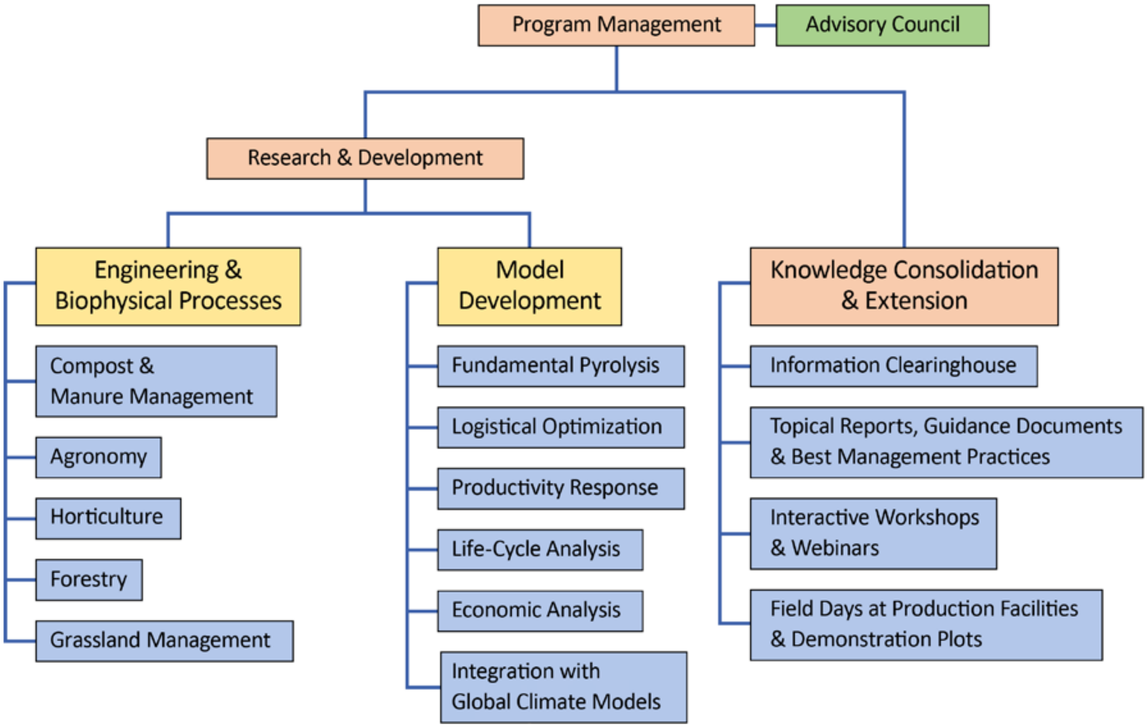

Figure ES-6. *Proposed long-term coordinated research and development program structure showing major groupings of activities.*

To have the desired impact, the research program should remain highly engaged with other researchers, biochar practitioners, stakeholders, and the general public—and information must also flow from these entities to the research program. To this end, we propose a major three-part effort towards *knowledge consolidation and extension:* 1) establishment of an online information clearinghouse for biochar information; 2) development of topical reports compiling scientific knowledge generated by the program together with that of others active in biochar technology R&D, as well as documents describing best management practices; and 3) launching an interactive outreach effort involving workshops and webinars to ensure that the program is actively engaged with, and responsive to, stakeholders and the general public.

Near-Term Market-Focused Research and Development. Knowledge developed in the long-term coordinated research program would also help guide near-term (one to three year) efforts focused on overcoming barriers to market development. Specifically, these efforts will 1) *develop protocols and specifications to ensure product consistency and appropriate use of biochar* (for example, a new certification standard for the US that would combine a C-sink estimate, categories of certification based on end-use, and a classification/labelling system); 2) *measure air pollutant emissions factors associated with biochar production* to help refine regulatory approaches; 3) *construct and facilitate application of algorithms that support market valuation of the ecosystem services provided by the use of biochar technology* including climate change mitigation, soil health, air quality improvements, and water storage; and 4) *conduct pilot studies and demonstrations for regional market development* (Figure ES-7*).* In order to support regional markets, we recommend a focus on near-term research and pilot- or larger-scale demonstrations of biochar technology, showing how biochar can generate direct economic value when used to address specific problems (e.g., soil acidity, low water-holding capacity, fire-hazard reduction, mined land reclamation, composting odors and efficiencies, and storm-water filtration) as well as the development of new high-value C-based products and materials (e.g., catalysts, battery electrodes, and reductants for specialty metallurgical operations).

Figure ES-7. *Biochar loaded for transport to regional markets. (Photo: Karl Strahl)*

Infrastructure to Support Business Development. Scaling up biochar production and application will require a robust private sector, and infrastructure to support business development in this still nascent area will be important. We propose that efforts focus on: 1) fostering business formation through direct assistance to businesses to develop partnerships and to provide planning tools as well as technical, regulatory, and financial aid; 2) training a diverse workforce through support of student and summer internships, on-the-job training, and formal education from high school through to college undergraduate and post-graduate levels; and 3) developing customer awareness through surveying stakeholders regarding current barriers to more widespread biochar production and use Once the product needed by the customer has been identified, we recommend the funding of marketing campaigns targeted at both wholesale and retail customers. Information from biochar businesses and potential end users could be used to align priorities for long-term research projects as well as near-term research and development projects and public policy campaigns. Implementation of the business-support infrastructure would involve strengthening the two primary trade organizations for the biochar industry (*International Biochar Initiative*, *United States Biochar Initiative* [IBI, USBI]) as well as potentially creating an entirely new organization, tentatively named the *Endowment for Biochar-Based Community Development (EBBCD)*, whose purpose would be to provide financial support for the infrastructure-building activities outlined in this section as well as some of the near-term research and development activities.

Collaborative Policy Development. The fourth major priority is focused on development of policy to support the growth of a sustainable biochar industry. Policy development efforts would depend heavily on improvements in scientific knowledge as well as work in the other priority areas. A key focus in this area is *price support for ecosystem services,* either directly through subsidies and tax credits or indirectly through policies that tax or otherwise raise the cost of undesirable alternative economic decisions. Examples of these types of price supports for the key ecosystem services provided by biochar technology include:

- **Climate change mitigation.**
  Direct: Payment of C-storage and GHG offset credits to biochar producers and practitioners that account for decreases in emissions based on full life cycle of production and use.

  Indirect: Levy a tax or fee on the CO_2e content of fossil fuel at the point where it enters the economy (wellhead, mine, port-of-entry).

- **Improvement of soil health.**
  Direct: Payment of credits to producers and practitioners for adoption of practices that improve soil health (similar in many ways to carbon storage credits). Governments or other organizations interested in promoting these practices could develop financial instruments to raise funds that would then be used to subsidize changes in farming and ranching practices.

- **Improvement of air quality and human health.**
  Direct: Insert clauses in publicly funded fire-hazard reduction contracts that recognize and reward the improved air quality provided by biochar technology relative to other biomass-removal practices (open burning of slash piles, controlled burns).

  Indirect: Levy a tax or fee on open-burning practices as part of the permitting process. A similar tax or fee could be levied on overstocked forested lands having high potential for wildfire.

- **Water storage.**
  Direct: Water storage brings economic benefits by enhancing plant productivity on lands where biochar is applied. In addition, the enhancement of water storage capacity by biochar can help minimize the size of flooding events. In specific areas where flooding is an issue, a policy by which national, state, and local flood-control districts would directly pay upstream landowners to apply biochar to their soils, could make sense.

Another area of focus involves *development of appropriate environmental permitting instruments* related to biochar production to protect the environment without penalizing pyrolysis-based conversion of biomass to biochar. Among permitting hurdles, air quality deserves attention. Above, we recommended funding to develop and consolidate the scientific understanding needed to create these new regulatory instruments. We recommend that funding be provided to the biochar industry trade organizations (IBI and USBI) to engage and work collaboratively with federal, state, and local regulatory agencies in the creation of these instruments.

We envision a four-stage collaborative process for *implementation* of recommended policy changes, led by the biochar industry trade organizations. The stages are as follows: 1) engage a diverse range of potential stakeholders in a conversation about what needs they see, the types of policies they prefer to address these needs, and their ideas of how best to proceed; 2) share relevant research results with this group of interested stakeholders; 3) form stakeholder coalitions to address and promote specific policy changes; 4) undertake promotional activity to implement and enable the new policy by developing general public support as well as the support of key government agencies and local, state, and federal legislators.

We provide further descriptions of the major recommended funding priorities in Chapter 3.

SECTOR-FOCUSED FUNDING PRIORITIES

Biochar technology is not monolithic. Rather, it is a complex ecosystem of approaches involving a variety of biomass feedstocks, biochar production methods, and scales of operation. To address this diversity, we organized the workshop participants into five working groups, each focused on a specific sector in the biochar technology universe. Discussions in the working groups explored the challenges and opportunities faced by their sector and provided recommendations for funding strategies to advance biochar technology in the context of their specific circumstances and goals.

Each working group generated a report summarizing their discussions. We distilled the insights from these sector-focused working groups in order to identify industry-wide challenges and opportunities and arrive at the major funding recommendations provided in Section I of the overall workshop report. The five sector-focused working group reports comprise Section II of the workshop report. Within Section II, Chapters 4-6 describe three complementary approaches to biochar production from woody forestry residues. Chapters 7 and 8 describe biochar production and use associated with municipal solid waste and agricultural systems. An introduction to each of these sector-focused chapters is provided in the paragraphs that follow.

Chapter 4: Place-Based Biochar Production, describes systems in which biochar is produced at a location for use at that location. Place-based biochar is an important part of ongoing fuel reduction and vegetation management projects intended to reduce the risk of catastrophic fire and improve soil productivity. A critical aspect of place-based biochar production is engagement with a variety of stakeholders for widespread deployment across the landscape. Typically, these systems are labor-intensive manual operations with no long-distance transportation of feedstocks. Biochar production may occur on the landscape using small, portable, low-tech units (~200-300 tons dry biomass per year, 20-55% C-conversion efficiency), mobile carbonizers (up to ~13,000 tons dry biomass per year, 5-15% C-conversion efficiency), or managed piles (~4-6% C-conversion efficiency).

Figure ES-8. *The Ring of Fire kiln is portable and used for place-based biochar production (Photo by Kelpie Wilson)*

Chapter 5: Moderate-Scale Biochar Production Across Forested Landscapes, focuses on mobile (relocatable) biochar production systems converting 1,000-100,000 tons of dry biomass per year to biochar (~5-55% C-conversion efficiency). These systems are often operated in or near forested landscapes (e.g., at forest landings) and generally involve transport of feedstocks over distances of less than 50 miles (commonly less than 10 miles). This scale has seen recent technological developments as entrepreneurs have deployed stand-alone mobile technology or incorporated these technologies into existing forest products manufacturing businesses. Biochar produced through moderate-scale production is generally produced as a value-added product to be transported to markets.

Figure ES-9. *This relocatable gasification system was set up for Redwood Forest Foundation, Inc. in Andersonia, California in 2017 and is an example of a moderate-scale system. (Photo: Arne Jacobson)*

Chapter 6: Centralized Biochar Production Facilities, describes industrial biomass systems in which biomass is transported to centralized facilities, carbonized at large scales, and processed into value-added products. Processing capacity at centralized facilities is usually greater than 100,000 tons of dry biomass per year (20-50% C-conversion efficiency). Biomass hauling distances are generally greater than 15 miles. Technologies in this category include biomass power plants modified for biochar recovery while generating bioenergy (20-35% C-conversion efficiency), and rotary kilns (24-50% C-conversion efficiency). Centralized production can achieve efficiencies of scale not attainable at place-based and moderate scales but requires a steady supply of feedstock within a reasonable transport distance. These facilities require high capital investment and must maintain a high level of operational efficiency to minimize costs.

Figure ES-10. *This biomass power plant, which has been modified for biochar production and uses forest residues from high fire hazard areas as feedstock, is an example of a centralized biochar production facility. (Photo: Josiah Hunt)*

Chapter 7: Biochar Production and Use at Municipal Compost Facilities, examines the potential benefits arising from the co-location of biochar production systems at municipal compost facilities that process a large amount of woody material. Large pieces of woody material do not compost readily and thus can serve as a feedstock for biochar production. When this biochar is then added to fresh compost feedstock prior to the composting process (co-composting), multiple benefits occur. In many instances, emissions of greenhouse gases and odor during composting decrease as does the time required for the compost to mature. Further, the properties of the co-composted product are improved making it more suitable for use in horticultural and agronomic applications. Chapter 7 also explores some of the relevant considerations for this type of integration including production technology, process technology, and permitting considerations.

Figure ES-11. *Biochar amended compost, steaming on a cold and sunny winter morning. West Marin Compost, Nicasio, California. (Photo: Josiah Hunt)*

Chapter 8: Agricultural Use, focuses on the use of biochar produced from crop and forestry residues as a soil amendment. Agricultural soils have the potential to safely incorporate large quantities of biochar while increasing crop yield and soil health. And yet, in order for biochar-based practices to be widely adopted, it is paramount that farmers have the ability to predict, with reasonable accuracy, the agronomic responses to biochar applications, a capability that does not yet exist despite the proliferation of biochar research. This chapter outlines recommendations aimed at resolving the agronomic-response knowledge gaps and using that knowledge to build more accurate cropping-systems models that can operate at local, regional, and national scales. This chapter also provides some examples of prescriptive, yield-focused uses for biochar in agriculture.

Figure ES-12. *Outside of Spokane, Washington, wheat growth is dramatically increased in soil amended with biochar (8 tons per acre, top right inset), compared to that grown in unamended soil (bottom left inset). (Photo: Kristin Trippe)*

Table ES-1. *Biochar production processes.*

Process	Sector[1]	Daily Capacity Input of Feedstock per Unit (BD tons/d)[2]	Carbon-Conversion Efficiency (%)[3]	Capital Cost	Labor Cost
Top-Lit Conservation Burn Piles	Place-based	1 - 20	4 - 6	Minimal	Medium
Flame Cap Kilns	Place-based	0.13 - 2.0[4]	20 - 55	Very low	High
Portable/Modular Field Units[5]	Place-based, Moderate	1 - 130	5 - 55	Low to Medium	Medium
Industrially Integrated Units[6]	Moderate, Centralized Facility	0.75 - 60	5 - 53	Low to Medium	Low to Medium
Rotary Kilns	Moderate, Centralized Facility	48 - 240	24 - 50	Medium to High	Medium
Dedicated Bioenergy Plants[7]	Centralized Facility	0.9 - 24[8]	20 - 35[9]	High	Medium

[1] Sectors are defined in Sector-Based Funding Priorities, above.

[2] Capacity: BDt = bone dry tons, 200 lb dry/cubic yard;

[3] C-conversion efficiency = 100*(tons biochar C/ton biomass C)

[4] Operations typically use up to eight units at a time.

[5] Portable air curtain incinerators/carbonizers, portable/modular retorts and gasifiers

[6] Combined heat & biochar, heated augers, fixed-location gasifiers.

[7] Wood boilers with capture/clean-up of re-injection ash

[8] This represents the portion (1.5% to 3%) of the total biomass feedstock consumed that is needed to maintain power output during biochar production. Total biomass conversion capacity ranges from 60 to 800 BDt/day and is mainly converted to bioenergy (heat and electricity).

[9] Uncertain due to variable fractions of biochar recovered and remaining in bottom ash under different operating conditions, but likely no higher than gasification.

CROSS-CUTTING TOPICS

We focused the first two sections of this report on the overall and sector-specific strategic funding recommendations of the workshop. However, we also identified a need to provide short reviews of several cross-cutting topics that touch on every sector of biochar technology. Section III, therefore, consists of four heavily referenced chapters that review the supply of biomass feedstocks in the Pacific Northwest, the technologies associated with biomass handling and biochar production, and the issues related to air quality permitting. Short introductions to these topical chapters follow.

Chapter 9: Biomass Supply, summarizes regional estimates of biomass supply (agricultural, municipal, and forestry residues) with a focus on Washington and Oregon, though national estimates are also provided. The Pacific Northwest contains ample amounts of low- and no-value woody residues, largely from forest-harvest operations, that are currently burned as slash piles. Different harvest, transport, and pricing scenarios affect the assessment of available forestry biomass. Compared to forestry residues, much smaller amounts of agricultural residues and urban woody biomass are also potentially available.

Chapter 10: Biomass Handling, examines considerations related to gathering, comminution (reduction of particle size), and transportation, as they relate to the three main scales of biochar production from woody biomass. Handling the biomass before it is converted to biochar can comprise a substantial cost for biochar systems.

Chapter 11: Biochar Production, explores thermochemical conversion processes typically used for biochar systems: pyrolysis, gasification, and combustion, and co-products resulting from these processes. Further, to provide context, we describe categories of equipment most relevant to this report including capacity, thermochemical processes used, and status of each technology. Table ES-1 provides a summary of the type of information provided in this chapter.

Chapter 12: Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems, describes one of the most complex regulatory issues that biochar producers face. In this chapter, we list the air emissions that may be of concern for regulators and summarize the permitting process.

MAXIMIZING THE CARBON VALUE

Biochar technology can play an important role in helping to mitigate climate change. While other technologies will also be needed, a recent estimate suggests that up to one-third of the total drawdown of atmospheric-C needed to stabilize the Earth's climate system can be provided by a long-term, aggressive, sustainable implementation of biochar technology[3]. For this to happen, however, the biochar industry will need significant investment by governments, NGOs, and private capital to resolve the remaining technical, financial, and regulatory barriers that currently slow its advance.

Climate change, however, is not the only issue we face, nor is it the only issue that biochar technology can address. Recent wildfires in the western U.S. and resulting property damage and air quality concerns underscore the importance of improving forest management. A clear opportunity exists for the implementation of biochar technology to also address wildfire risk, restore degraded land, improve forest and soil health, enhance ecosystem services, and revitalize rural economies.

The discussions stimulated by this workshop have identified the key investments needed, over the course of a decade, to generate "game-changing" advancements in biochar technology. If we are to meet the challenges we face, these investments will need to start very soon. By maximizing the C value of biochar technology as we proceed, we will help ensure that the many benefits we seek are obtained.

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[3] *Amonette, J.E., H. Blanco-Canqui, C. Hassebrook, D.A. Laird, R. Lal, J. Lehmann, D. Page-Dumroese. 2021.* Integrated biochar research: A roadmap. *Journal of Soil & Water Conservation 76(1):24A-29A.* https://doi.org/10.2489/jswc.2021.1115A