

# Biomass *to* Biochar

Maximizing the Carbon Value



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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		
<i>AAPFCO</i>	Association of American Plant Food Control Officials	<i>DMDS</i>	dimethyl disulfide
<i>ACI</i>	air curtain incinerators	<i>EBC</i>	European Biochar Certificate
<i>ARS</i>	USDA Agricultural Research Service	<i>EBBCD</i>	Endowment for Biochar-Based Community Development
<i>ATC</i>	Authority to Construct	<i>EPA</i>	U.S. Environmental Protection Agency
<i>BACT</i>	Best Available Control Technology	<i>EPCRA</i>	Emergency Planning and Community Right-to-Know Act of 1986
<i>BD</i>	bone dry	<i>EQIP</i>	Environmental Quality Incentives Program
<i>BRDI</i>	Biomass Research and Development Initiative	<i>ERC</i>	Emissions Reduction Credits
<i>BPS</i>	biochar production systems	<i>EU</i>	European Union
<i>BUC</i>	Biomass Utilization Campus	<i>FDA</i>	U.S. Food and Drug Administration
<i>C</i>	carbon	<i>GHG</i>	greenhouse gas
<i>CAGR</i>	compound annual growth rate	<i>GRACEnet</i>	Greenhouse gas Reduction through Agricultural Carbon Enhancement network
<i>CARB</i>	California Air Resources Board	<i>GREET</i>	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
<i>CDEA</i>	California Department of Food and Agriculture	<i>Gt</i>	gigatonne or billion metric tonnes
<i>CEC</i>	cation exchange capacity	<i>GT</i>	gigaton or billion U.S. tons
<i>CEQA</i>	California Environmental Quality Act	<i>GWP<sub>100</sub></i>	global warming potential
<i>CFLRP</i>	USDA USFS Collaborative Forest Landscape Restoration Program	<i>ha</i>	hectare
<i>CGIAR</i>	Consortium of International Agricultural Research Centers	<i>HAP</i>	hazardous air pollutants
<i>CH<sub>4</sub></i>	methane	<i>HCl</i>	hydrogen chloride
<i>CHAB</i>	combined heat and biochar	<i>HPLC</i>	high performance liquid chromatography
<i>CISWI</i>	Commercial and Industrial Solid Waste Incineration Units	<i>HRA</i>	health risk assessment
<i>Cl<sub>2</sub></i>	chlorine gas	<i>IBI</i>	International Biochar Initiative
<i>CO</i>	carbon monoxide	<i>IPCC</i>	Intergovernmental Panel on Climate Change
<i>CO<sub>2</sub></i>	carbon dioxide	<i>KMnO<sub>4</sub></i>	potassium permanganate
<i>CO<sub>2e</sub></i>	carbon dioxide equivalent	<i>LCA</i>	life cycle assessment
<i>CO<sub>2e</sub> T<sup>-1</sup></i>	carbon dioxide equivalent per ton	<i>LCFS</i>	Low Carbon Fuel Standards
<i>CY</i>	cubic yard	<i>LTBR</i>	long term biochar research



<i>MMBtu</i>	1 million BTU British Thermal Unit.
<i>MSW</i>	municipal solid waste
<i>Mt</i>	megatonne or million metric tonnes
<i>MT</i>	megaton or million U.S. tons
<i>MW</i>	megawatt (can refer to energy content of biomass going into the plant as well as energy output by the plant)
<i>MWe</i>	megawatt of electrical output (by an energy plant)
<i>NAAQS</i>	National Ambient Air Quality Standards
<i>NEPA</i>	National Environmental Policy Act
<i>NGO</i>	non-governmental organization
<i>NH<sub>3</sub></i>	ammonia
<i>N<sub>2</sub>O</i>	nitrous oxide
<i>NO</i>	nitric oxide
<i>NO<sub>2</sub></i>	nitrogen dioxide
<i>NO<sub>3</sub><sup>-</sup></i>	nitrate
<i>NOx</i>	generic term for the nitrogen oxides that are most relevant for air pollution, namely nitric oxide and nitrogen dioxide
<i>NRCS</i>	Natural Resources Conservation Service
<i>NREL</i>	National Renewable Energy Laboratory
<i>NSR</i>	New Source Review
<i>NWFP</i>	Northwest Forest Plan
<i>O<sub>3</sub></i>	ozone
<i>ODEQ</i>	Oregon Department of Environmental Quality
<i>ODT</i>	oven dry ton
<i>OFRI</i>	Oregon Forest Resources Institute
<i>OMRI</i>	Organics Materials Review Institute
<i>OSWI</i>	Other Solid Waste Incinerators
<i>PAH</i>	polycyclic aromatic hydrocarbons

<i>Pb</i>	lead
<i>PM</i>	particulate matter
<i>PM<sub>2.5</sub></i>	particulate matter with a diameter 2.5 micrometers or smaller
<i>PM<sub>10</sub></i>	particulate matter with a diameter of 10 micrometers or smaller
<i>PNW</i>	Pacific Northwest
<i>ppbv</i>	parts per billion by volume
<i>PSD</i>	Prevention of Significant Deterioration
<i>PTO</i>	Permit to Operate
<i>RCPP</i>	Regional Conservation Partnership Program
<i>RFRS</i>	Remote Forest Research Stations
<i>ROG</i>	reactive organic gases
<i>SEPA</i>	State Environmental Policy Act
<i>SO<sub>2</sub></i>	sulfur dioxide
<i>TPY</i>	tons per year
<i>USBI</i>	United States Biochar Initiative
<i>USDA</i>	United States Department of Agriculture
<i>USFS</i>	United States Forest Service
<i>VOC</i>	volatile organic compounds
<i>wt. %</i>	percent by weight

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# Executive Summary

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***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 ( $\text{CO}_2\text{e T}^{-1}$ ) 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<sup>1</sup>,

<sup>1</sup> Amonette, J.E. 2021. *Technical Potential for CO<sub>2</sub> 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)<sup>2</sup>.

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 the 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<sub>2</sub> removal from the atmosphere. In particular, monetizing CO<sub>2</sub> 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)

<sup>2</sup> A-ECY. 2021. Washington State Greenhouse Gas Emissions Inventory: 1990-2018. <https://apps.ecology.wa.gov/publications/Summary-Pages/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

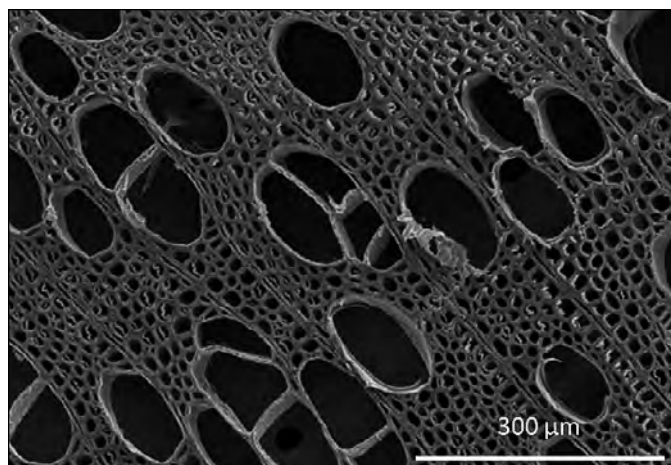
To advance biochar systems in the Pacific Northwest and beyond, 40 biochar practitioners and researchers representing industry, academia, non-profit, and government sectors convened virtually over several months starting in April 2020 with the following objectives:

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.

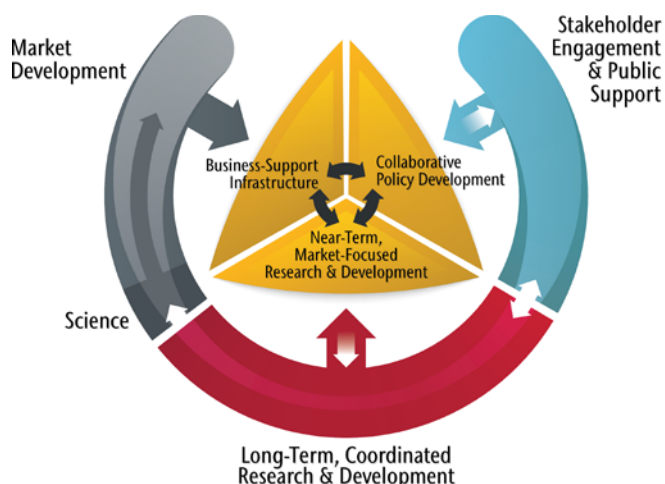
## RECOMMENDED FUNDING STRATEGIES

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

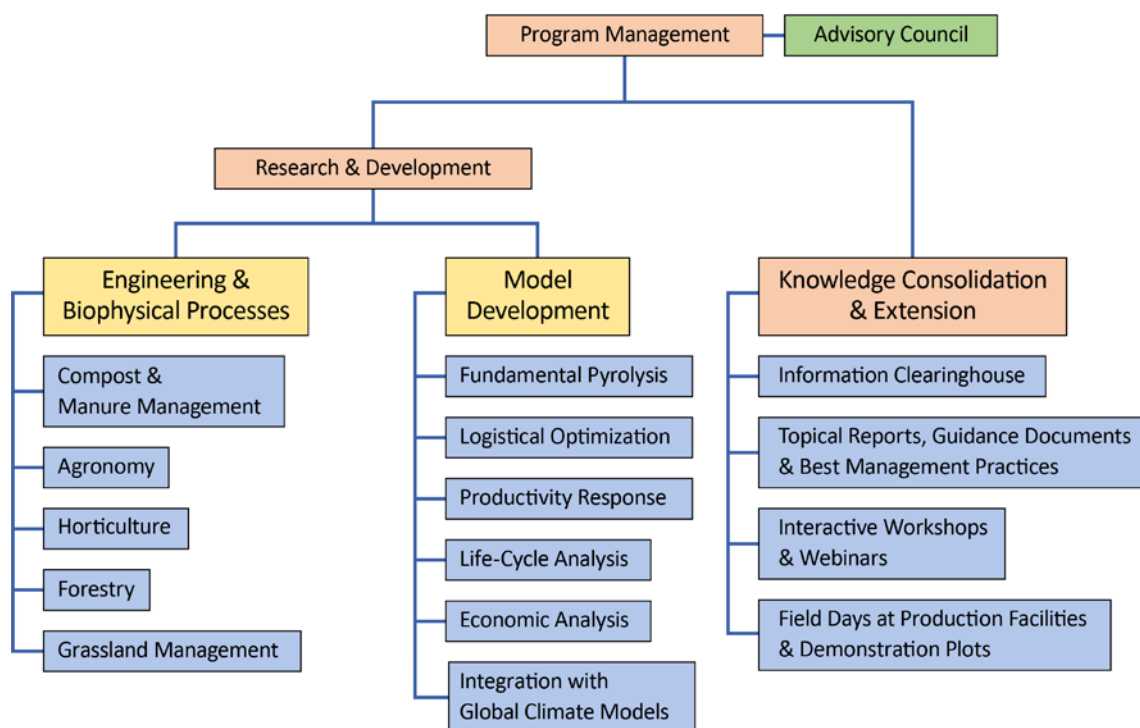


**Figure ES-5.** Conceptual diagram of the relationships between the four major priority funding areas recommended by the workshop. Long-term coordinated research & development (in red) provides the foundational science and engineering needed to support development of biochar technology. Three closely 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)

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.

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<sub>2</sub>e 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).

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



**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.

*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.

*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-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)



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



**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 <sup>1</sup>	Daily Capacity Input of Feedstock per Unit (BD tons/d) <sup>2</sup>	Carbon-Conversion Efficiency (%) <sup>3</sup>	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 <sup>4</sup>	20 - 55	Very low	High
Portable/Modular Field Units <sup>5</sup>	Place-based, Moderate	1 - 130	5 - 55	Low to Medium	Medium
Industrially Integrated Units <sup>6</sup>	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 <sup>7</sup>	Centralized Facility	0.9 - 24 <sup>8</sup>	20 - 35 <sup>9</sup>	High	Medium

<sup>1</sup> Sectors are defined in Sector-Based Funding Priorities, above.

<sup>2</sup> Capacity: BDt = bone dry tons, 200 lb dry/cubic yard;

<sup>3</sup> C-conversion efficiency = 100\*(tons biochar C/ton biomass C)

<sup>4</sup> Operations typically use up to eight units at a time.

<sup>5</sup> Portable air curtain incinerators/carbonizers, portable/modular retorts and gasifiers

<sup>6</sup> Combined heat & biochar, heated augers, fixed-location gasifiers.

<sup>7</sup> Wood boilers with capture/clean-up of re-injection ash

<sup>8</sup> 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).

<sup>9</sup> 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<sup>3</sup>. 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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<sup>3</sup> 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>





## SECTION I: **Summary**

This section summarizes the overarching workshop discussions, with a focus on defining 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.

In **Chapter 1**, we describe the collective environmental and social motivation for this work. We also explain the need to capture value from biochar production systems in order to advance their development.

**Chapter 2** identifies the major challenges to development of the biomass-to-biochar supply chain.

**Chapter 3** provides a set of recommended funding priorities for overcoming these challenges and capitalizing on current opportunities.



## CHAPTER 1:

# Introduction

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**Figure 1.1.** Biochar (right) is the carbon-rich solid produced by heating biomass (left) under low-oxygen conditions. (Photo: Biomacon)

*Biomass* is renewable, carbon (C)-rich organic matter derived from recently living plants and animals. *Biochar* is the C-rich solid produced by heating biomass under low-oxygen conditions to a temperature where its chemical structure transforms to a more stable form similar to that found in graphite (Figure 1.1). The conversion process spontaneously releases more energy than it consumes; this bioenergy can be used to generate electricity and as a source of heat. Like coal char (i.e., char made from coal, which is fossilized C-rich organic matter), biochar can be burned to generate energy, but this offers little or no benefit relative to burning the original biomass. Instead, biochar has greater value as an amendment to soil, to compost, and even to construction materials, where it can store C for long periods of time while providing other benefits specific to these applications [71]. By virtue of the large quantity of biomass available in agricultural and forestry residues, the generation of bioenergy during the conversion, and the enhanced stability of the C in biochar relative to the original biomass, large-scale conversion of biomass to biochar is considered an

### Biochar by the Numbers

In the 17 contiguous western states, about 94 Mt or 104 MT (1 Mt = 1 million metric tonnes; 1 MT = 1 million tons) of biomass containing 42 Mt (46 MT) of C can be sustainably harvested each year from agricultural, forestry, and municipal residues [113]. Assuming a high but practical C-conversion efficiency of 49% and about 50 years to reach the maximum production rate [121], biochar containing 1,700 Mt (1,874 MT) C could be produced over the course of a century. Addition of this biochar to cropped soils in the region would increase the soil C content in the plow layer by half (i.e., by 0.75% C after accounting for some loss of biochar to oxidation). Assuming biochar C behaves similarly to native soil C, the plant-available water storage capacity in these soils would increase by nearly 4 million acre-feet [78]. Use of the heat released during biochar production to generate electricity would yield 2,500 MW of power, support 250 biomass power generation facilities distributed throughout the region, and account for 1.5% of the region's electricity production. Taken over a century, the combined impact of biochar technology in the western United States could yield a climate offset of 9.2 Gt (10.1 GT) carbon dioxide equivalent (CO<sub>2</sub>e; 1 Gt = 1 billion metric tonnes; 1 GT = 1 billion tons). ■

important negative-emission technology that can help mitigate climate change [5, 25, 69, 79, 102, 121]. (See sidebar: “Biochar by the Numbers” on page 3.)

Over the last decade and a half, a number of major research efforts in the western U.S. and Pacific Northwest (PNW), and a diverse set of smaller efforts, have explored the potential for biomass conversion to biochar and bioenergy to improve forest and agricultural soil health and to draw down atmospheric C (See sidebar: “Biochar Research in the Pacific Northwest” on page 4). The U.S. biochar industry has been led by producers in the western U.S. since its inception [38, 48], and the PNW offers a particularly promising context for scaling up biochar production since the region has large quantities of potential feedstocks (e.g., forestry biomass, urban wood waste, crop residues) located in close proximity to large areas of diverse agricultural production with potential to support and benefit from biochar application. As of August 2020, the biochar industry in the Pacific Coastal States included eleven suppliers in Oregon, nine in Washington and 25 in California, with much of the biochar produced as a byproduct of biomass to bioenergy plants. The region is also rich in industry and academic expertise and in the engagement of both government agencies and non-governmental organizations (NGOs). Interest in scaling up is widespread as indicated by the 2019 passage of a Senate Joint Memorial in Washington State ([S-0339.1](#)) in support of biochar research and use, only the second such memorial in the U.S. after a similar resolution was passed in Colorado in 2017

([SJR17-002](#)). In November 2020, the first C credits for biochar production in the U.S. were issued to a biochar supplier in California after a long cooperative effort involving a local sawmill and support from regional, national, and international biochar industry organizations [87].

These strengths position the western U.S., and the PNW in particular, to fully develop biochar’s potential for climate change mitigation, forest health improvement and wildfire risk reduction, soil health, and ecosystem services, and rural community revitalization. While biochar production and use in the region has steadily gained momentum during the last decade, the industry has remained relatively small. Strategic investment will overcome existing barriers and magnify the value proposition, maximizing positive impacts for communities and ecological systems.

## BACKGROUND

In April 2020, forty biochar practitioners and researchers representing industry, academia, NGOs, and government participated in a virtual workshop to chart a roadmap for future development of biochar technology in the PNW and beyond. Most of these individuals were from the western U.S., primarily Washington, Oregon, and California. The group met over several months to consider the exciting opportunities that conversion of biomass to biochar offers. They explored how biomass is harvested, converted to biochar, and applied, and where operational changes and funding could significantly magnify biochar’s contributions.

### Biochar Research in the Pacific Northwest

Starting in 2007, the Washington State Department of Ecology funded a sustained effort focused on the beneficial use of waste biomass to produce bioenergy and biochar [23, 24, 40-44, 47, 56]. Early work on biochar in Washington State was also supported by the Paul G. Allen Family Foundation as part of the [Climate Friendly Farming Project](#) [123]. Subsequently, USDA National Institute of Food & Agriculture funded the [Northwest Advanced Renewables Alliance](#) for five years. The focus of this work was on the production of jet fuel from biomass, but several reports were

generated on the availability of woody biomass from forest health and fire hazard reduction treatments [7] and mill residues [10] as well as on the conversion of a residual biomass waste product (lignin) to a form of biochar that could substitute for activated C [36]. Another major effort was a three-year project funded by the Biomass Research and Development Initiative (a collaboration between the U.S. Department of Energy and the USDA) called [Waste to Wisdom](#). This project, which involved 16 organizations throughout the western U.S., focused

on making better use of forest residues from harvesting and thinning operations by exploring new methods of feedstock development and biomass conversion in the context of rigorous sustainability analysis [52]. In addition to these large projects, many individuals, companies, and smaller research groups in the region have explored different feedstocks, equipment configurations, and biochar applications to address a wide diversity of issues associated with conversion of biomass to biochar and lay the foundation for a vibrant biochar-based economy. ■



## Examples of Biochar Technology in the Pacific Northwest

**Place-based biochar production:** Small (usually less than 500 tons per year [TPY] woody biomass feedstock), labor-intensive manual operations with short distance transportation of biomass, biochar used on-site.

**Moderate-scale biochar production:** Temporary biochar production sites, often at forest landings, using skid-mounted trailer-sized conversion systems (usually 1,000 to 100,000 TPY woody biomass feedstock) and involving some transport of biomass (less than 50 miles).

**Large-scale, centralized biochar production:** Permanent biomass conversion facilities (usually greater than 100,000 TPY woody biomass feedstocks) often with bioenergy production, and one-way hauling distances less than 100 miles.

**Biochar integrated with municipal composting facilities:** Production of biochar from woody biomass collected from solid waste and its use as a catalytic agent in composting of organic wastes.

**Biochar used in agricultural soils:** Biochar produced at any scale from woody biomass, manures, and crop residues and usually used as a soil amendment. Agricultural uses represent an important market due to the large volumes and potential climate mitigation and soil health benefits. ■

The main objectives of the workshop were to:

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.

This report summarizes the collective discussions related to these two objectives and provides a prioritized list of recommendations for investors, philanthropists, policy makers and others interested in helping the region maximize benefits from biochar production and application. While most of the authors of this document are grounded in the PNW and are familiar with biochar production and application in this regional context, many of the recommendations in this report are applicable elsewhere in the U.S and even globally.

The report contains three major sections:

**Section I** (Chapters 1-3) summarizes the overarching workshop discussions, with a focus on Objective 2. In the remainder of Chapter 1, we describe the collective environmental and social motivation for this work. We also explain the need to capture value from biochar production systems in order to advance their development. Chapter 2 identifies the major challenges to development of the biomass-to-biochar supply chain, while Chapter 3 provides a set of recommended funding priorities for overcoming these challenges and capitalizing on current opportunities.

**Section II** (Chapters 4-8) contains a detailed analysis of five representative examples of biochar production and use in the PNW, summarizing the group's work on Objective 1 (see sidebar: *"Examples of Biochar Technology in the Pacific Northwest"* on page 5).

**Section III** provides supporting overviews on the topics of biomass supply (Chapter 9), biomass handling (Chapter 10), biochar production (Chapter 11), and air pollutant emissions and air emissions permitting for biochar production systems (Chapter 12). In these chapters, we also refer readers to more detailed references, where appropriate.

## VISION AND POTENTIAL

Development of a robust biomass-to-biochar pathway offers a unique opportunity to simultaneously address four pressing societal and environmental needs: 1) Climate change mitigation; 2) Forest health improvement and wildfire risk reduction; 3) Soil health and ecosystem services; and 4) Rural community revitalization. Further development of the biomass-to-biochar supply chain to realize these benefits depends on monetizing the value of these products or services while focusing on sustainable design and implementation of biochar systems.

### Climate Change Mitigation

Climate change is one of the most pressing global challenges of our era. Negative consequences are already being felt across the globe. Our own region is no exception, with drought and wildfire being two dominant and closely related impacts [80]. The events of 2015 marked a dramatic turning point that provides a preview of future climate in the PNW [76 p. 1041]. After several years of drought, record low snowpack from warmer winter temperatures resulted in water scarcity during the summer months, affecting agriculture, hydropower, and recreation, and contributing to a then-record wildfire season, which

was subsequently eclipsed in dramatic fashion by the wildfires of 2020. Over the long term, warmer winters also help lay the groundwork for larger wildfires by increasing the risk of insect infestations that ultimately result in extensive tracts of dead, standing timber.

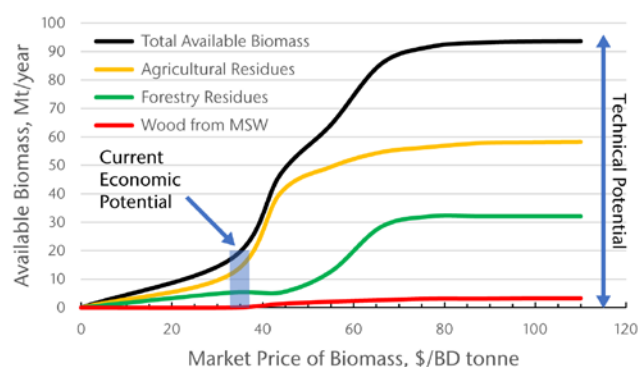
Since 2015, the economic cost associated with the wildfires in Washington, Oregon, and California alone have totaled more than \$60 billion, far exceeding the \$40 billion cost of wildfires in the entire U.S. for the preceding 35 years [80]. The loss of life has been equally disastrous, with 209 lives lost in the fires in Washington, Oregon, and California since 2015 compared with 184 lives lost nationally between 1980 and 2015 [80]. The effects of climate change are not felt equally by communities across the Northwest or nation, with low-income communities and those dependent on natural and cultural resources facing greater threat [76 p. 1062]. Without mitigation, these climate-related changes are expected to continue to impact the economy, health, and welfare of the region and the nation [76].

To mitigate these impacts, the scientific consensus calls for numerous strategies to reduce anthropogenic emissions and sequester or draw down atmospheric C [101, 102]. These strategies include, among others, direct air capture of carbon dioxide (CO<sub>2</sub>), afforestation and reforestation, enhanced weathering of silicate minerals, changes in land management to increase stocks of soil organic C, and thermal conversion of biomass to bioenergy with C capture and sequestration or with co-production and storage of biochar. *Given the enormity of the task and the variety of situations, all these strategies will likely be needed.* Biochar has been recognized by the Intergovernmental Panel on Climate Change (IPCC) for its potential to contribute significantly to C sequestration [85 p. 398]. In the report *Getting to Neutral: Options for Negative Carbon Emissions in California*, biochar is one of the five classes of promising negative emissions technologies evaluated with the goal of full deployment by 2045 [8]. Importantly, biochar technology offers the potential for widespread and relatively near-term deployment.

The climate change mitigation potential of biochar technology depends on a number of factors, primarily the supply of biomass that is harvested, but also the fraction of the C in the original biomass that ends up in the biochar (i.e., the C efficiency), the alternative fate of the biomass C, the stability of the biochar after conversion, the native fertility of the soils to which biochar is

applied, and whether the heat generated is used to offset fossil-C sources of energy (and if so, the carbon intensity of the existing energy supply) [25, 121].

The amount of biomass available for conversion to biochar and bioenergy is bracketed by two numbers. The larger of these is the *technical* potential, which is the amount of biomass that could be harvested sustainably regardless of the cost of doing so. The smaller number is the *economic* potential, which is the amount that can be harvested sustainably and profitably at a given market price for biomass (Figure 1.2). Due, in part, to whether and how sustainability guidelines and economic costs are considered, estimates of available biomass vary widely and are not without controversy [25]. In Figure 1.2 we show estimates for the harvest of biomass from agricultural, forestry, and municipal waste streams in 17 western U.S. states that were generated by the 2016 Billion Ton Report [113] using strict sustainability guidelines coupled with economic considerations assuming biomass market prices between \$33 and \$110 per bone dry<sup>1</sup> (BD) tonne<sup>2</sup> (between \$30 and \$100 per BD ton). Agricultural residues account for most of the available biomass (between 62% and 86%), followed by forestry residues (between 11% and 35%), and finally wood from municipal solid waste (between 0% and 3.5%). The estimated total technical potential is 94 Mt (104 MT) of dry biomass (42 Mt [46 MT] of C) and is reached at market biomass prices above \$80 per BD tonne (\$73 per BD ton). At the current biomass market price (ca. \$35 per BD tonne or \$32 per BD ton, [114]), the estimated economic potential is about 20 Mt (22 MT) of dry biomass (9 Mt [10 MT] of C). Price support at \$40 per BD tonne (\$36 per BD ton) biomass<sup>3</sup> for C sequestration by biochar could



**Figure 1.2.** Estimated available biomass for 2021-2030 from agricultural, forestry, and municipal sources in 17 Western States at different market prices [113]. Current biomass market price for forestry residues is about \$35 per bone dry tonne [114]. Technical potential is reached at about \$80 per bone dry tonne.

1 "Bone dry" and "oven dry" are both units used for biomass and are essentially interchangeable. Here we opt to use bone dry and abbreviate as BD.

2 In this report we provide values in both metric tonnes (1,000 kg; 2,204.6 lbs) and U.S. tons, as both units appear in the biochar literature.

3 Which is equal to \$83 per tonne [\$75 per ton] C, or \$23 per tonne [\$21 per ton] CO<sub>2</sub>e



**Figure 1.3.** Biomass One in Medford, Oregon is a biomass power plant generating 32.5 megawatt electrical (MWe) (28.5 MWe goes to the grid). This plant consumes 200,000 tons per year of dry biomass and can recover 50,000 cubic yards of biochar annually (Photo: Karl Strahl)

increase biomass harvest several fold. An increase in the market price of just \$6.25 per BD tonne (\$5.67 per BD ton) biomass to \$41.25 per BD tonne (\$37.41 per BD ton)<sup>4</sup> could double the economic potential.

Biochar production systems vary substantially [40, 128] and, as a result, their climate impacts also vary. Key considerations include the C efficiency of the biomass transformation, the emissions of greenhouse gases (GHGs) and particulates during the process, and whether the heat generated replaces fossil-C sources of energy. During biochar production, the highest C efficiencies of 30% to 55% are seen with slow pyrolysis<sup>5</sup>. Combustion, on the other hand, typically yields C efficiencies below 3% but releases three times as much heat that, if captured, can be used to generate electricity and for other purposes.

Biochar production technologies with higher C efficiencies, by definition, have lower emissions. These emissions, however, will vary in their content of methane (CH<sub>4</sub>) and soot, both of which have more powerful impacts on the climate than CO<sub>2</sub>. The main goal, then, is to eliminate emissions of CH<sub>4</sub> and soot during production, leaving CO<sub>2</sub> as the only GHG emitted. Methods to complete the conversion of CH<sub>4</sub> and soot to CO<sub>2</sub> before release to the atmosphere have

been developed. These methods typically involve some form of post-pyrolysis combustion process such as funneling gases through an afterburner, re-injection of gases into the pyrolysis system, or harnessing natural convection processes to create a combustion zone above the pyrolysis zone as in flame-cap kilns and conservation burn piles.

Co-generation of electrical power and other uses of the heat released during biochar production make eminent sense from a climate-change mitigation perspective but are not always economical, particularly in areas with inexpensive hydropower, such as the PNW. Due to the capital costs involved, successful implementation usually occurs with large, centralized facilities (typically 20 MW capacity or larger) having easy access to the electrical grid and a stable supply of biomass within a 50-mile economical transportation range (Figure 1.3; see *Chapter 6: Centralized Biochar Production Facilities*). Smaller combined-heat-and-biochar systems for use with schools and light industry are practical in many instances. The climate impact of these applications depends on the fossil-C intensity of the energy supply that they replace. Supplanting electricity generated by coal will have a large beneficial impact whereas little or no benefit would be obtained by replacing solar, wind, or nuclear power.

<sup>4</sup> Which is equal to an increase of \$13 per tonne [\$12 per ton] C, or \$3.50 per tonne [\$3.17 per ton] CO<sub>2</sub>e

<sup>5</sup> Pyrolysis is a thermal decomposition process in the absence of oxygen that separates components of biomass into gases, liquids, oxygenated compounds, and solids. Slow pyrolysis is a form of pyrolysis characterized by heating of biomass at a slow rate (around 5-7 °C per minute). See *Chapter 11: Biochar Production*.



Once biochar is made, it needs to be stored in a location where it will not release C to the atmosphere rapidly—ideally, release rates of less than 10% per century are desired. Biochar can be added to construction materials such as asphalt, where it replaces some of the fossil C, or concrete, where it replaces some of the aggregate, and in both of these instances it can improve the mechanical properties of the materials [1, 26, 29, 50, 115, 124, 126]. The most common storage location for biochar, however, is in soil, which already contains an enormous amount of C—an estimated 1,500 gigatonne (Gt; 1 billion metric tonnes) (1,650 GT; 1 billion tons) of soil organic C is stored in the top meter of soils [9, 97], compared to roughly 270 Gt (298 GT) C stored in standing forest stocks globally [33] and 885 Gt (976 GT) C currently present as CO<sub>2</sub> in the atmosphere [82].

Biochar's unique structure resists biological and chemical degradation. Thus, biochar persists in the soil for hundreds to thousands of years, much longer than the original feedstock [71]. The C sequestration potential is greater in temperate climates than in tropical ones, with C stability depending on biochar properties and soil characteristics as well as climate [85]. In many instances, biochar application enhances native soil C stocks through “negative priming” in which labile C forms complexes involving the biochar and mineral soil particles (See sidebar: “*Biochar's Impact on Native Soil Carbon Stocks*” on page 8). “Positive priming,” where application of biochar enhances mineralization (loss) of existing soil organic C stocks, has been reported in some cases [85], but this effect seems to be temporary and, over the long term, shifts to negative priming [11, 12, 28, 54, 66, 99, 129].

Adding biochar, particularly to highly weathered soils, acidic soils, and sandy soils, can have beneficial effects on plant growth [27, 61, 64]. Highly weathered soils benefit from the increase in nutrient-retention capacity offered by the large surface area of biochar. Acidic soils benefit from the highly basic nature of many biochars, which act similarly to lime. Sandy soils benefit from significant increases in water-holding capacity (as well as nutrient-retention capacity). Biochar amendments thus offer a way of restoring degraded lands by improving their fertility. Increased productivity, in turn, provides a positive feedback loop by generating more biomass that can be converted to biochar.

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

### Biochar's Impact on Native Soil Carbon Stocks

Over the past decade, a significant body of work has been devoted to the question of how biochar amendments affect the native organic C (SOC) stocks in soils. Most of this work involved laboratory incubations for a few weeks to a few years and led to a consensus that during the early stages after biochar amendment a net loss of SOC can occur, and that loss certainly occurs after addition of fresh organic matter with the biochar. Thereafter, the observed net change in SOC in the laboratory studies is either neutral or negative, meaning that, over the long run, biochar amendments either have no impact on SOC or they actively promote SOC accumulation.

For century-scale estimates of the changes in SOC, one modeling study [122] and three natural-analog studies [12, 54, 66] at abandoned charcoal production sites in Europe provide consistent estimates of the degree of SOC accumulation that can be expected. The results suggest that, over a century or more, on the order of a 30% to 60% increase in SOC occurs in sub-humid temperate-zone soils to which biochar has been applied. Field studies in similar soils in the U.S. [11] and Australia [100, 119] show rapid accumulation during the first decade followed by slower accumulation as a new equilibrium is reached. These long-term studies sow optimism regarding the ability of biochar to increase native SOC stocks but require further research to confirm. ■

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<sub>2</sub> equivalents per tonne of bone dry feedstock (t CO<sub>2</sub>e BD tonne<sup>-1</sup>), meaning that the climate impact is beneficial (resulting in less CO<sub>2</sub> 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 [25, 94, 95].

Because the impact of GHGs changes with time due to their different atmospheric residence times relative to CO<sub>2</sub>, 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

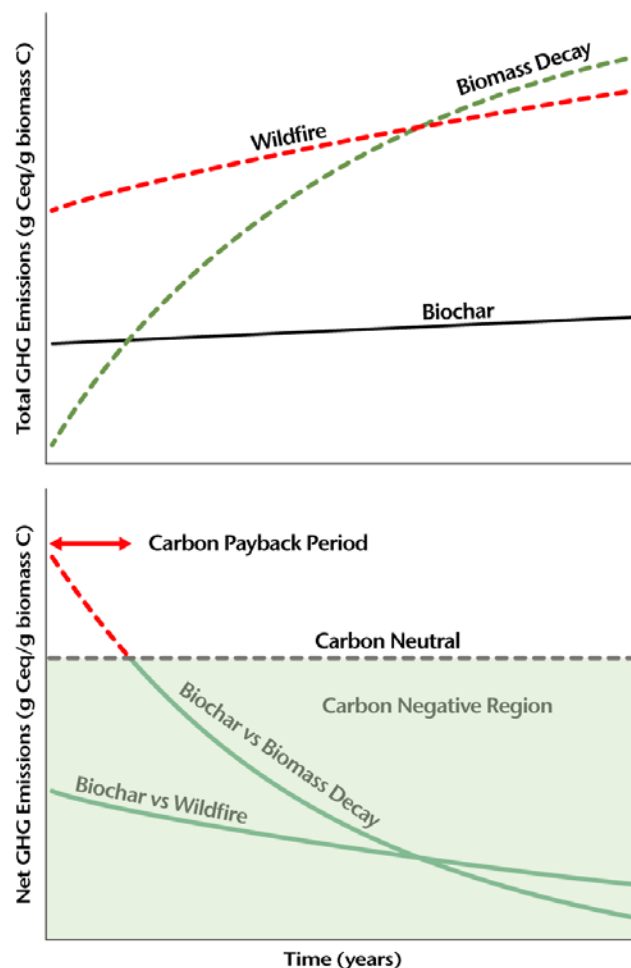


biomass fates (Figure 1.4). In the top panel, total GHG emissions per unit of biomass C are shown for each of the three biomass pathways. The bottom panel shows the net GHG emissions for biochar relative to the alternative biomass pathways. In this hypothetical example, when biochar is compared to wildfire, 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.

The overall climate-mitigation impact is thus tied strongly to the sustainability of the harvesting practices and the ultimate fate of any products. When biochar is made from biomass waste byproducts – such as lumber mill wastes, forest management byproducts, defensible space clearing (for wildfire risk reduction), orchard and vineyard prunings, food-processing waste such as fruit and nut pits and shells, urban or suburban yard wastes, and livestock manure—the utilization for energy and biochar can be C negative (Figure 1.4). Compared to baseline disposal through on-site open burning or spreading of wood chips, production of biochar and bioenergy by modern low-emission facilities yields significant climate benefits resulting from: (a) the displacement of the need for the combustion of fossil fuels for comparable energy production, and (b) the avoidance of the disposal of the biomass wastes through either open-pile burning, or in-field decay and decomposition, either of which may release significant amounts of CH<sub>4</sub>.

On average, using biomass to make biochar has a larger potential to mitigate climate change than combusting the same biomass for bioenergy because it sequesters C belowground, stimulates crop productivity, and reduces or avoids GHG emissions by soils [121]. This advantage for biochar is particularly true in areas such as the PNW that rely primarily on hydropower, a low-C energy source [2]. Bioenergy, however, has a greater climate change mitigation potential in some areas where coal dominates energy production and the crops do not respond to biochar amendments due to high soil-fertility levels. In the future, as the C-intensity of the energy supply decreases, the climate-mitigation potentials of both biochar and bioenergy will decrease, but that of bioenergy will decrease about 2.5 times more rapidly than biochar [121].

With respect to the global climate mitigation impact of biochar production, several detailed estimates of the biochar technical potential that invoke strong



**Figure 1.4.** Two stages in a hypothetical time-sensitive LCA of biochar technology. (Top) Total GHG emissions of biochar and two alternative fates of the same woody biomass feedstock (decay in place and wildfire). (Bottom) Net GHG 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.

sustainability criteria to determine the available biomass supply were provided by Woolf et al. [121]. The lowest of these estimates, which represented the available biomass with little change from current practices or technology, was about 3.7 Gt (4.1 GT) of CO<sub>2</sub>e per year. The highest, which was termed the “maximum sustainable technical potential,” was 6.6 Gt (7.3 GT) of CO<sub>2</sub>e per year. These estimates covered the range of 7% to 12% of the global anthropogenic emissions in 2012 and are probably about twice as large as the corresponding economic potentials. Biochar technology thus can be a critical strategy for mitigating climate change alongside other strategies. Meanwhile, it offers the potential for many other beneficial impacts on specific sites and communities where it is used.

## Wildfire Risk Reduction and Forest Health Improvement

In western U.S. forests, fire suppression and changes in forest management have resulted in heavily stocked forests that are at higher risk of damage by disease, insects, and high temperature wildfire – and of reduced ecosystem resilience in the face of climate change [55, 117 p. 22-31]. More frequent wildfires and resulting poor air quality are expected to increase respiratory illness in the coming decades [83 p. 519]. Fine particulate matter due to 2020 wildfires been linked to increases in COVID-19 cases [127]. Oregon, Washington, and California are among the top 10 states for the number of properties at high risk due to wildfires [116] and were states that experienced devastating wildfires in 2020 (Figure 1.5).

Practices aimed at reducing wildfire risk include removal of woody biomass from areas surrounding structures and thinning stands with unnaturally high density resulting from fire suppression. Haugo et al. [53] estimate that a change in forest structure is needed in approximately 40% of the forested area in Oregon and Washington with thinning or controlled (low-severity) burns as the most commonly needed treatment. Thinning forests results in large quantities of low-value forest biomass (Figure 1.6). In the 17 contiguous western states of the U.S., up to 32 million BD tonnes (35 million BD tons) of forest waste and residues could be sustainably produced each year from thinning and normal tree-harvesting operations [113; Figure 1.7].

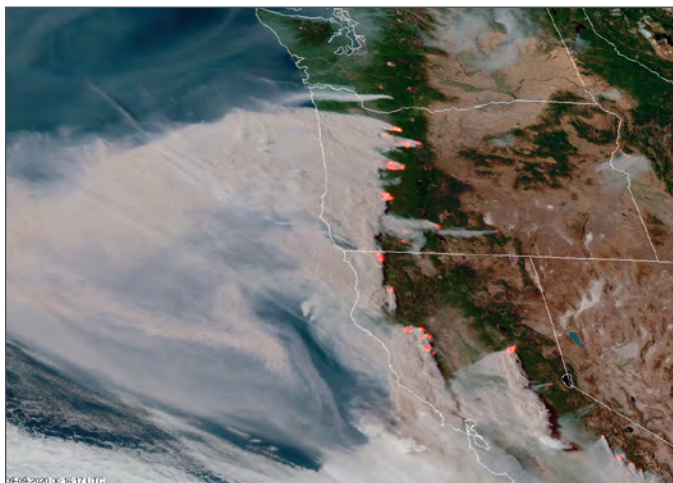
When harvesting and thinning operations occur, the resulting forest waste and residues are typically burned in slash piles (Figure 1.8), a practice that vaporizes nutrients, generates air pollutants [18], alters soil

properties [19], and forms scars on the landscape that are prone to exotic plant invasion [65]. Embers from slash pile burns can cause hundreds of wildfires each year across the western U.S.

While thinning and controlled burns have ecological and social value, they are expensive and difficult to implement on a large scale. The commercialization of biochar from forest residuals could lower the cost of wildfire risk-reduction treatments, making it possible to treat more acres with scarce public funding and maximize benefits to air quality and public safety.

Meanwhile, producing biochar from this low-value woody biomass instead of burning it could benefit forest ecosystems. The biochar could be used on-site to improve forest soils, increase nutrient retention, and mitigate compacted soils, erosion, and revegetation challenges created by forestry activities. It could also be exported for application to agricultural soils, reclaimed mine-land soils, or other purposes. Thus, biochar technology could significantly increase the air quality and decrease the associated health issues stemming from pile-burning in the PNW [92].

The climate impact of addressing forest-health issues with biochar production could be significant. Amonette [4] estimated available biomass, biochar production, and CO<sub>2</sub> drawdown potential for six forest harvest scenarios in Washington State. Depending on scenario, 5 to 8.5 million BD tonnes (5.5 to 9.4 million BD tons) of biomass was available for biochar production at centralized facilities yielding 100 to 340 Mt (110 to 375 MT) of biochar C production and 450 to 1,400 Mt (496 to 1,544 MT) CO<sub>2</sub>e offsets over 100 years. When on-site production at the forest landing was included, these values doubled. Applying the same approach here to



**Figure 1.5.** Smoke and fires in the western U.S. visible from space on September 9, 2020. (Photo: rammb.cira.colostate.edu NOAA Satellites and Information)



**Figure 1.6.** Slash pile resulting from fuel reduction treatment near Flagstaff, Arizona. (Photo: Han-Sup Han)





**Figure 1.7.** Logs and slash piled near Flagstaff, Arizona covering four acres at a depth of approximately 20 feet. This pile was assembled but never taken off-site due to the lack of forest products manufacturing facilities nearby and was subsequently consumed in the 2019 Museum Fire. (Photo: Markit! Forestry)

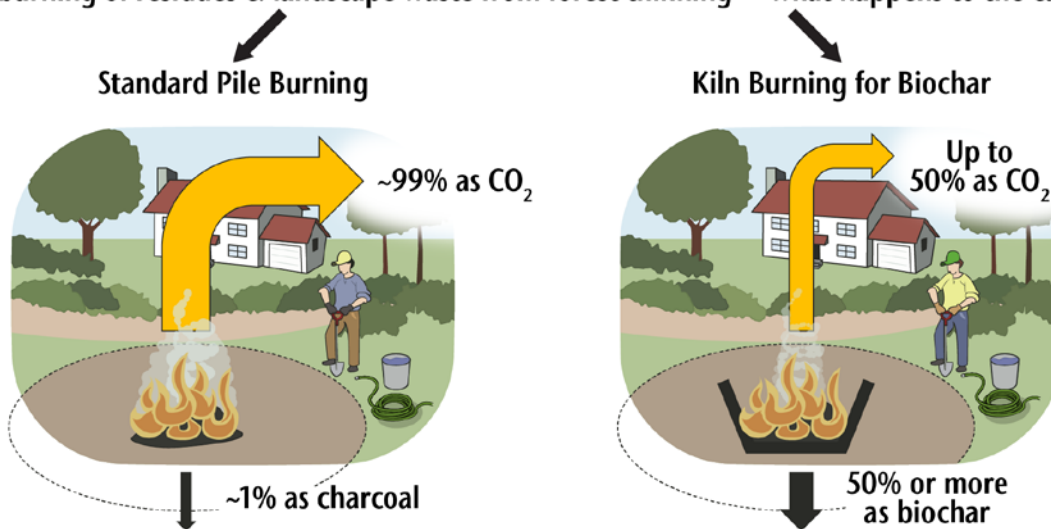
the 32 million BD tonnes (35 million BD tons) of forest biomass potentially available to centralized facilities in the 17 western states [113], suggests that 620 Mt (684 MT) biochar C and 2,400 Mt (2,646 MT) CO<sub>2</sub>e offsets<sup>6</sup> could be generated over 100 years.

While this report is focused primarily on forestry residues due to the large potential for biomass contribution from states like Washington and Oregon, agricultural residues also provide a large source of feedstock for biochar systems, as much as 58 million BD tonnes (64 million BD tons) in the 17 western states. Burning of agricultural residues is less common now than it was historically, but where burning is used it can have negative air quality impacts, impacting human health. The dry organic fraction of municipal solid waste (e.g., waste wood) provides another source of feedstock (as much as 3.3 million BD tonnes [3.6 million BD tons] in the 17 western states). When used to manage municipal solid wastes, biochar production could re-capture the C value of these wastes and reduce the negative impacts of landfilling.

## Soil Health and Ecosystem Services

Biochar can help avoid, reduce, and reverse land degradation—a condition that afflicts over a quarter of Earth's ice-free land [63, 85]. Due to its high porosity, extraordinary surface area, and surface-active properties, biochar has been applied to restore soil chemical, biological, and physical properties of agricultural,

### Pile burning of residues & landscape waste from forest thinning — what happens to the carbon?



**Figure 1.8.** Burning in a biochar kiln instead of a standard burn pile converts as much as half of the C in wood waste into biochar. Biochar lasts for hundreds to thousands of years in soil, benefiting forest health and sequestering C. (Figure adapted from CalFire)

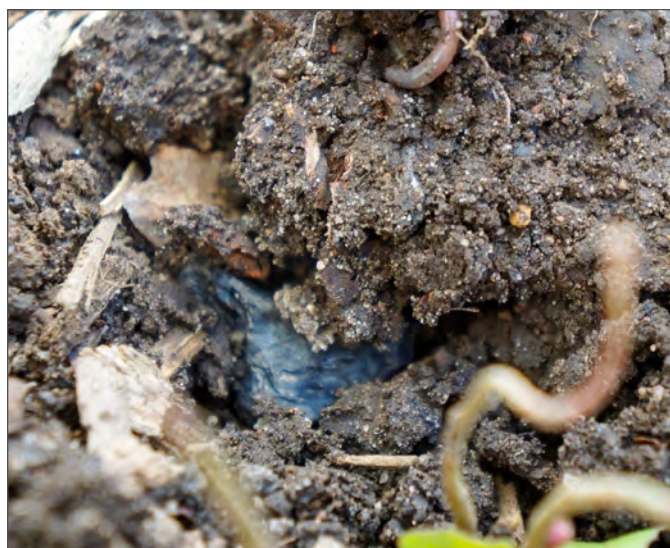
<sup>6</sup> The offsets for the 17 western states are higher in proportion to the biochar C generated than for Washington State because they have a 50% higher average fossil-C intensity of their energy supply.

rangeland and forestry soils that have been degraded from overuse, mismanagement, or natural disasters [6, 84]. It has also been used for remediation of severely degraded soils associated with abandoned mine land and drilling sites.

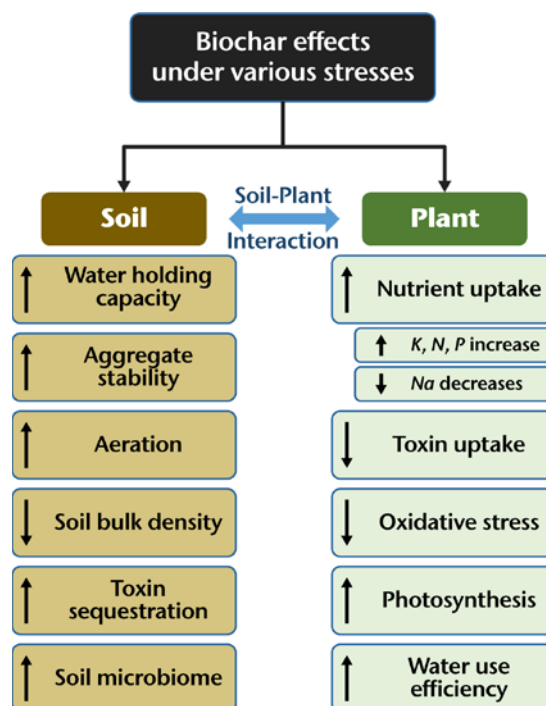
Biochar application has been studied most extensively in agricultural soils, where improvements in soil and ecosystem health are usually seen [64, 73, 74, Figure 1.9]. In general, biochar amendments to soil increase nutrient availability [62], enhance microbial activity [35, 49, 108], decrease nutrient losses by leaching [13, 57, 67, 105], and minimize off-site movement of pesticides [46, 51, 73]. Mechanisms responsible for these observed outcomes include decreases in bulk density, and increases in soil pH, cation-exchange capacity [67, 107], porosity, water-holding capacity [3, 30, 75, 86, 93, 125], and aggregation [15]. Over the long term, biochar amendments increase active (labile) soil organic matter [11, 12, 54, 66, 119], which helps stabilize the granular structure of the soil [110, 118] and thereby improve tilth (the physical condition of soil).

These generalizations aside, the specific effect of biochar applications on soil health depends on the characteristics of the biochar, which are impacted by feedstock and production process [59], and on the soil type, with nutrient-poor soils showing the greatest improvements [27, 32, 61]. Several studies [31, 37, 60] have also indicated potential for biochar to increase plant resistance to biotic and abiotic stresses through mechanisms shown in Figure 1.10, but this depends strongly on the biochar-soil-crop system. One can thus imagine instances, such as the application of a high pH biochar to a high pH soil, where application of biochar would lead to a decline in soil health, at least in the short run. Consequently, to ensure optimal results, application decisions need to be based on accurate characterization of the biochar and the soil with consideration given to the type of vegetation involved.

Soil health improvements, ideally, result in crop yield improvements. A wide range of impacts from decreased yield to increased yield have been reported in the literature, resulting from the wide variety in feedstocks, production and post-production methods used, and crops and soils to which resulting biochar is applied [27, 32, 61, 106]. Yield improvements from biochar tend to be more likely in nutrient-poor soils with more modest gains in nutrient-rich soils. Since the economics of biochar are marginal and are often tied to assumptions regarding duration of yield benefits, a better understanding of the dynamics at play could significantly improve ability to target applications



**Figure 1.9.** Biochar amendment can provide a host of benefits to soil. (Photo: Brennan Pecha)



**Figure 1.10.** Model of how biochar affects soil, plants, and soil-plant interactions under stressed conditions (Source: Gang 2018 [39])

of specific biochars to situations that offer the best potential for return on investment [27, 32, 61, 106].

Recently, growing regional, national, and global interest in “regenerative agriculture” has sparked interest in the role that biochar (along with reduced tillage, cover cropping, amendments, and other agricultural practices) can play in revitalizing soil health and building stores of C in agricultural topsoil that has



been degraded over time [14, 20, 34, 68, 103]. Biochar can contribute to current efforts to improve soil health by public and private organizations (e.g., Soil Health Institute, Soil Health Partnership, USDA, NRCS, The Nature Conservancy). And biochar can contribute to other ecosystem services in agricultural systems, such as by retaining nutrients in soil, thereby reducing nutrient pollution, and protecting waterways. As an indication of the level of interest in biochar, more than 100 innovative western U.S. farmers volunteered acreage on their farms for a U.S. Biochar Initiative (USBI) proposal to demonstrate and monitor biochar use following release of a new NRCS Conservation Practice Standard for soil carbon amendments [77, 111].

Biochar can benefit forest soils as well. Application of biochar to forest soils generally enhances soil chemical, physical, and microbial properties [72]. A recent meta-analysis found that biochar application to woody plants could result in an average 41% increase in biomass, with most pronounced results in early growth stages [109]. Though many of the relevant studies focus on deciduous forests, there are some studies of evergreen forests relevant to the region. For example, Sarauer et al. [96] found that biochar applied to forest soil in the inland Northwest increased soil C by as much as 41% and Palviainen et al. [88] showed that biochar increased the diameter of pine trees in Finland by 25% and height by 12% during the first three years after application. Keeping forests healthy and resilient improves their productivity as well as their ability to provide clean air and water, habitat for wildlife and reduced fire risk. In addition, because healthy temperate-zone forests remove about 3.4 tonnes CO<sub>2</sub> per hectare (1.4 tons CO<sub>2</sub> per acre) each year from the atmosphere (2.6 Gt [2.9 GT] CO<sub>2</sub> per year globally) [45, 89, 90], of which 69% to 92% is ultimately stored in forest soils [97], they are a critical tool in confronting climate change.

## Revitalizing Rural Communities

More difficult to quantify, but equally important in the discussion of value provided by scaling up of biochar systems is the value of revitalizing rural communities. Rural communities across the U.S. are on balance older and poorer, with persistently slower rates of employment growth compared to urban areas [112].<sup>7</sup> In the Northwest, many communities that had historically

relied on forest-based industries to support livelihoods have experienced dire economic circumstances in recent decades due to widespread closures of lumber and paper mills from the 1990s through the present.

In the early 1990s, the Northwest Forest Plan (NWFP) established a new forest management framework for the 24 million acres of federal forestland in Washington, Oregon, and California within the range of the Northern Spotted Owl and shifted 11 million acres of federal forestland from timber production to old-growth forest protection, dramatically accelerating a decline in timber harvests that was already underway.<sup>8</sup>

The dramatic drop in federal timber harvests combined with ongoing automation and industry concentration led to a wave of mill closures across the region. In 1980, for example, 405 lumber mills operated in Oregon. In the following three decades, two thirds of these mills closed. By 2007 there were only 58 mill towns in Oregon. For the region's small communities, a mill closure represents a serious economic blow to community employment and economic well-being [22]. Between 1990 and 2000, socio economic well-being indicators were more likely to drop in communities near federal forestlands in the NWFP area than in communities farther away, and the majority of communities scoring low on a socioeconomic well-being index were within five miles of a federal forest [21].

The economic fallout from the NWFP spawned numerous efforts that combined rural job creation and federal forest restoration, including Jobs in the Woods, stewardship contracting, American Recovery and Reinvestment Act, and the Coordinated Landscape Restoration Program. More recently, Good Neighbor Authority provided federal agencies with additional funding, greater authority, and the administrative flexibility to pursue the twin goals of ecological and community resilience. While these programs did not specifically include biochar development, they represent federal investment and community engagement approaches that can inform the pathway to a robust biochar industry.

Many communities in the PNW that were historically dependent on forest products continue to struggle with a lack of economic opportunity and associated social and community issues. Biochar production can provide a durable economic development engine with a manu-

<sup>7</sup> Rural America includes 14% of the Nation's population but accounted for only 4% of employment growth between 2013 and 2018. The rural poverty rate was 16.4% in 2017, compared with 12.9% for urban areas. In the U.S., 19% of the rural population was 65 years or older, compared with 15% in urban areas.

<sup>8</sup> For example, in Oregon, in 1989, almost 5 billion board feet of timber was harvested in Oregon on federal forests. Harvests dropped to less than 200 million board feet in 2001 and averaged less than 330 million board feet per year during the most recent decade.

facturing component that can support the economy of struggling rural communities, while reducing wildfire risk and improving forest health (See sidebar: *“Helping Rural Economies”* on page 14). Economic revitalization is particularly important in light of the economic disruption due to the Covid-19 pandemic.

## Capturing Monetary Value in Biochar Systems

To realize these societal benefits, biochar production must be economically viable. This depends on monetizing the value of goods and services that are provided.

Currently, the two products that have been reliably “monetized” include the thermal energy (heat) that is produced during the pyrolysis process, and the biochar. The thermal energy can be used within a facility to reduce energy costs and can also be used to generate electrical power that can be sold. Valuation of thermal energy is relatively straightforward and depends on existing energy prices. Valuation of biochar as a soil amendment, on the other hand, is more difficult due to variable impacts and a need to identify the niches where biochar is most likely to provide economic benefits to applicators.

Meanwhile, monetizing other benefits has been a challenge to date. Monetizing the value of forest restoration and fire-hazard reduction deserves substantial attention due to the potential harm to communities and lives resulting from catastrophic fires in the West. Ultimately, it may be most likely that the other monetary benefits generated by biochar could help stretch existing public funds focused on forest restoration, enabling treatment of more acres.

Monetizing CO<sub>2</sub> removal from the atmosphere through C markets has significant potential to “tip the scales” toward overall economic viability of biochar production [25, 98, 104, 120]. Until recently, biochar producers in the western U.S. have not been able to take advantage of C markets and policies, even where such policies exist, such as Cap and Trade and the Low Carbon Fuel Standard (LCFS). Each potential market platform has different requirements that must be met before biochar can be recognized. Accessing these markets is an active area of work – one that could have substantial impacts if successful. One seminal success in this effort was achieved in November 2020, when C credits for biochar production were issued to a biochar supplier in California [87].

To give an idea of the potential economic impact of access to climate-related markets and policies we explore the impacts under two possible approaches.

## Helping Rural Economies

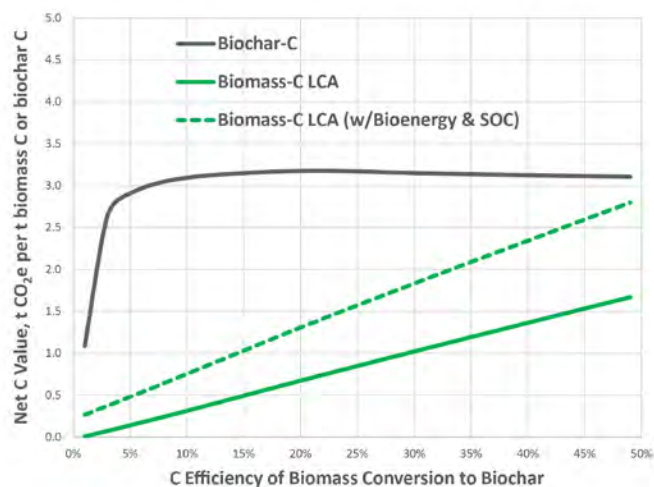
Small rural towns typically have abundant supplies of agricultural or forestry residues nearby that can be used as feedstocks for biochar/bioenergy production facilities. A typical wood gasifier facility could process 300,000 BD tonnes (331,000 BD tons) of biomass annually (34 BD tonnes [37 BD tons] per hour), from which 45,000 tonnes (49,600 tons) of biochar (at 15% efficiency) and 660,000 MWh of energy could be produced. With steam generation, the facility could supply 19 MW of electricity to the local grid, enough to power 15,000 homes, and still have 57 MW of thermal energy available for other purposes such as space heating of homes, businesses, and greenhouses. A plant of this size could provide 35 jobs and support 120 people. Additional jobs would be found in biomass procurement activities such as fire-hazard reduction operations in forests. Annual expenses would total \$19 million (capital \$6.6 million, labor and operations \$6.8 million, feedstocks \$6 million). Sale of the biochar at \$150 per tonne (\$136 per ton) and of the electricity at a wholesale price of \$30 per MWh would yield \$12 million in revenue. Additional revenue from C credits, higher value biochar products, or thermal energy for space heating would be needed. For example, at a C price of \$40 per tonne (\$36 per ton) CO<sub>2</sub>e, offsets from biochar-C and bioenergy could generate \$7.8 million. Sale of thermal energy at \$18 per MWh could generate \$9 million. Development of multiple product streams could help assure profitability.

A similar analysis for a slow pyrolysis facility (31.5% biochar efficiency) shows a slight profit from biochar and electricity sales alone. Potential revenue from sales of C credits at \$40 per tonne CO<sub>2</sub>e (\$14.5 million) and thermal energy (\$4.6 million) adds to this profitability. ■

The first, simpler approach, is agnostic with respect to the method of production and is used for most current C credit markets. This method bases the marketable climate offset on the properties of the biochar alone and thus does not consider the amount of biomass consumed or the possible beneficial use of the energy produced. Although it accounts for the decay of biochar in the soil over time, it does not account for any ancillary impacts on soil processes or native organic matter stocks. This approach yields remarkably consistent net C values of about 2 to 2.5 tonnes CO<sub>2</sub>e per tonne *biochar* at the time of soil application, and 1.8 to 2.3 tonnes CO<sub>2</sub>e per tonne biochar after 100 years [17]. Under these simple and verifiable conditions, C values of \$70 to \$150 per tonne (\$63 to \$136 per ton) CO<sub>2</sub>e could completely offset biochar production costs. Current market prices

are in this range. Using a value of 2 tonnes CO<sub>2</sub>e per tonne biochar (after 100 years) as an example, the European markets at 2020 prices would add approximately \$100 per tonne (\$91 per ton) of biochar value; California Cap and Trade could add \$40 per tonne (\$36 per ton); and the California and Oregon Low Carbon Fuel Standard could add \$400 per tonne (\$363 per ton) of economic value.

The second possible approach incorporates the C efficiency of the production process as well as the properties of the biochar and calculates net C value in terms of tonne CO<sub>2</sub>e per tonne biomass C [25,104,120]. Using this LCA-based approach with biomass data from Washington State<sup>9</sup>, estimates of net C values range from a low of about 0.14 tonnes CO<sub>2</sub>e per tonne biomass C at 5% C efficiency to a high of more than 1.5 tonnes CO<sub>2</sub>e per tonne biomass C when C efficiencies above 45% are attained (solid green line in Figure 1.11). Generation of electricity using process energy and consideration of impacts on soil C stocks and vegetative response increases these net C values by at least 60% (dashed green line in Figure 1.11). Although smaller than the near-constant net C value estimated on the biochar-C basis (dark grey line in Figure 1.11), these biomass-C values provide a truer representation of the C impact of biochar technology. Further, they reward high-efficiency producers, ensure maximum climate mitigation impacts from limited biomass resources, and provide a strong incentive for development of LCA-based C-market instruments.



**Figure 1.11.** Estimates of net C value for biochar systems in Washington State evaluated on the basis of biochar properties only (dark grey line) or with inclusion of C efficiency of biomass conversion (solid green line). The dashed green line adds the impacts of bioenergy generation and of biochar amendments on native soil organic C stocks.

<sup>9</sup> For a more in-depth discussions of biochar production and sustainability, see the International Biochar Initiative's Guiding Principles for a Sustainable Biochar Industry [58] and Garcia-Perez et al. [43].

Whichever approach is taken, consistent and standard biochar characterization methods and protocols must be developed and adopted before C markets can be accessed. Existing protocols (based on biochar properties alone) can be adapted to smooth the development process and lower costs. For example, an emerging C market platform that operates in the U.S. and Germany [17] includes biochar in their trading platform and requires either a European Biochar Certificate (EBC) or International Biochar Initiative (IBI) certificate for verification. In California, a reporting protocol for biochar is presently being adapted for submission to the Climate Action Reserve. If approved, bioenergy producers could register biochar compliance offset credits under the state's Cap and Trade program. The additional economic value generated could produce millions of C offset credits and greatly accelerate the utilization of biochar throughout California and beyond [16]. Work is still needed to develop protocols based on biomass C efficiency, which have great potential to stimulate further development of a sustainable biochar industry.

While achieving the promise of biochar systems requires economic viability, it also requires a continued effort to maximize the environmental and social aspects of sustainable biochar production and use, and minimize unintended negative consequences.<sup>9</sup> Important considerations include safety for production personnel and equitable labor practices, transparent operations and stakeholder relationships, feedstock choices and land use before production, C efficiency, GHG emissions, energy use, and output during production, C stability and application after production, and open sharing of knowledge.

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## CHAPTER 2:

# Key Challenges and Opportunities

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A number of substantial barriers to widespread commercialization of biochar, and current opportunities, informed our group's recommendations for investment. This chapter describes these key challenges and opportunities in more detail—the recommendations for investment are discussed in Chapter 3.

## ENGINEERING

Although biochar knowledge is expanding rapidly, engineering challenges remain throughout the production process. Much of the potential biomass for biochar production in the Pacific Northwest (PNW) is woody material from forested areas. Accordingly, the first challenge is to improve harvesting and handling of this material to allow biochar producers to access feedstock more efficiently, while furthering other land-management objectives. This includes moving away from the current practice of collecting biomass in slash piles and then burning it in the open. It also includes efficiently accessing the large quantity of “stranded biomass” that is currently left on the landscape, unavailable due to access issues or the expense of harvest and transport. A good start has been made on these challenges by the Northwest Advanced Renewables Alliance ([NARA](#)) and Waste to Wisdom projects [17] but much remains to be done.

Another major challenge is to design new biochar production systems that improve C efficiency, decrease net emissions of methane ( $\text{CH}_4$ ) and soot, and enhance economic performance over existing systems. In general, moderate- to large-scale (greater

than 30,000 tons per year [TPY] of feedstock) facilities are more economical to operate [17] and often have the flexibility to alter production modes from full bioenergy to a mixture of bioenergy and biochar depending on market conditions. The large-scale technology is mature and due to high capital costs, most likely to be deployed in areas where a constant supply of inexpensive biomass can be obtained. The greatest challenge is found in designing small-scale (less than 20,000 TPY feedstock) biochar production systems that match the technical and economic performance of the large-scale systems. Demand for improved small-scale systems is high according to surveys of small-scale biochar producers [16].



**Figure 2.1.** This biochar production unit<sup>1</sup> and loader are an example of moderate-scale biochar production. Here, biomass resulting from removal of invasive gorse is converted to biochar in Bandon, Oregon. Conversion to biochar inhibits the spread of the invasive plant. (Photo: U.S. Forest Service Region 6 State & Private Forestry)

<sup>1</sup> This equipment is being developed via Cooperative Research and Development Agreement (CRADA) between USDA-FS and Air Burners Inc. Development is based on U.S. patent 2018/0010043 A1.



**Figure 2.2.** The USDA Forest Service National Technology Development Center developed a biochar spreader that can be used to apply biochar to log landings or skid trails, seen here working on the Lubrecht Experimental Forest in Montana. This equipment can work on slopes up to 35%. (Photo: USDA Forest Service)

Integration of biomass harvesting systems with biochar production systems, particularly those located in the field at forest landings, is a prime example where design can have a direct impact on economics [12, 17] (see sidebar in Chapter 3: “*Designing Sustainable Biochar Systems*” and *Scenario 1* in Chapter 5). Because about half the harvested forest biomass is currently left at the landing due to transportation costs and market conditions [3, 4, 31], development of efficient small-scale production systems that can operate economically at forest landings will substantially increase the total amounts of biomass converted to biochar (Figure 2.1).

A third major engineering challenge is to improve methods of applying biochar to soils. In part, this effort involves identifying appropriate physical forms of biochar (e.g., particle size, dry solid, aqueous slurry) for each application setting. A second consideration is whether biochar is applied directly or as part of a mixture with other amendments such as compost or fertilizer. Additional considerations include determining the manner of biochar placement in soils (e.g., surface broadcast or banding, sub-surface injection). Coupling these considerations with the economic constraints associated with different application settings (agricultural, horticultural,

viticultural, pasture, rangeland, and forest) leads to a wide range of potential engineering challenges and solutions. Potential technical solutions include formulating solid and liquid forms of biochar that can be applied with existing systems such as air seeders, no-till and strip till equipment, and electrostatic sprayers. An example of this type of engineering is the biochar spreader technology developed by the U.S. Forest Service and Washington State University ([29]; Figure 2.2) who mounted a modified road-sand spreader on a log forwarder to apply pelletized or bulk biochar to skid trails and log landings.

A final major engineering challenge is to develop new opportunities to manufacture multiple value-added products from gaseous, liquid, and solid outputs [20, 35, 38]. In addition to development of novel products containing biochar, one key product that is rarely utilized outside of centralized facilities is the bioenergy embodied in bio-oil,<sup>2</sup> syngas,<sup>3</sup> and heat. In some biochar systems this heat is captured as electricity (e.g., boilers producing steam) or used to dry feedstocks, while in other systems, the heat is simply released because heat capture is not economical. In the PNW, this challenge is exacerbated by competition with inexpensive hydroelectricity. The net climate impacts of biochar production

2 A product resulting from thermochemical conversion of biomass in some cases. Bio-oil shows promise for use as a biofuel though it must be upgraded in order to be used directly as a transportation fuel. (<https://www.sciencedirect.com/topics/engineering/bio-oil>)

3 An abbreviation of “synthesis gas,” a gasification product, mostly from waste biomasses, consisting of a mixture of H<sub>2</sub>, CO, and CO<sub>2</sub> that could be used as a potential intermediate in the conversion of biomass into fuel. (<https://www.sciencedirect.com/topics/engineering/syngas>)



are more favorable when this energy is captured and used to offset fossil fuel energy. Further work is needed to optimize bioenergy capture and utilization at different scales of production, including capturing waste heat in smaller scale production systems.<sup>4</sup>

## SCIENTIFIC

The scientific challenges for biochar technology can be grouped into three major categories. The first is the impact of biochar amendments on soil-plant systems. Understanding this aspect is key to determining the potential economic benefit to adoption of biochar by agricultural and silvicultural producers. The second category relates to the overall impact of biochar technology on the Earth's climate system—from biomass harvesting through biochar production and ultimately biochar application. Because this nominally beneficial aspect is one that sets biochar apart from other uses of biomass, understanding the total impact is critical to justifying the development of carbon (C) markets that can provide the economic support needed for wide-scale adoption. The final category involves the use of biochar in composting operations. Here, substantial variability in emissions and plant responses is found, and scientific studies to clarify where biochar can make a beneficial difference are needed.

### Impacts on Soil-Plant Systems

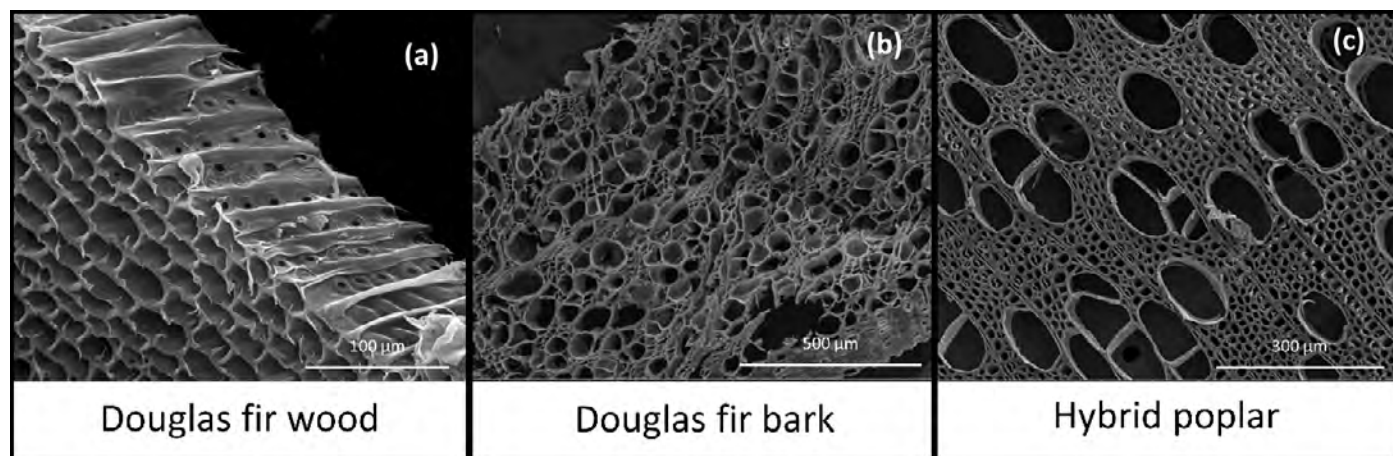
One of the primary challenges that biochar technology faces is that of being able to predict quantitatively, and at a local level, how particular

biochar amendments to soil affect the plants growing in that soil (Figure 2.3). Meeting this challenge will take the work of a decade or more, but a coordinated effort involving field trials with different biochars and soil-plant systems coupled with development of predictive models will likely provide the fastest route to this goal [5]. With robust models in place, best management practices can be developed for the myriad of potential settings where biochar can be used, thereby stimulating adoption of biochar as a mainstream technology. The bulk of research to date has been conducted in agricultural settings [11, 18, 19], but biochar application in horticultural, pastoral, range and forestry settings deserves further attention.

In agricultural systems, biochar sometimes, but not always, improves crop growth and yields [21]. Variability in results likely depends on the combination of biochar properties (source material and production conditions), soil type, and crop type. One challenge



**Figure 2.3.** Biochar impacts on plants grown in biochar-amended soil can vary greatly and likely depend on the specific combination of soil, biochar, and plant type. (Photo: Karl Strahl)



**Figure 2.4.** Micropores in biochar vary based on feedstock type and pyrolysis temperature. Shown are electron microscopy images of biochar made from some typical feedstocks: Douglas fir wood, Douglas fir bark, and 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.



to developing better mechanistic understanding of the interactions between biochar properties, soil type, and crop type is that some researchers report the study of biochar in a particular setting without discussion of the specific biochar properties that affect end-use suitability, such as chemical composition, porosity, pore-size distribution (Figure 2.4), and surface chemistry. Variability in these attributes results from differences in feedstocks, production parameters, and post-production treatments. Other challenges include the fact that physical and chemical properties of biochar in soils are not static, but instead change over time after application. Improved understanding of how these factors impact end uses in different climates and soil types could help lead to better identification of the situations in which biochar application will benefit agricultural and silvicultural crops. This knowledge, in turn, will facilitate broader acceptance and adoption of biochar by the agricultural community.

An essential component of mechanistic models for biochar-soil-plant systems would be the ability to quantify the influence of physiochemical properties of biochar on plant nutrient-use efficiency and nutrient leaching. Another essential component would be the ability to predict the size and half-lives of readily decomposed and highly stable biochar C pools, and the impact of biochar amendments on soil organic C stocks, cation exchange capacity, bulk density, porosity, redox potential, drainage, plant-available water, nutrient cycling, and microbial activity. While some of these factors would be of particular interest to growers, others could inform specific policy efforts aimed at increasing C storage or improving nutrient management.

Eventually, modeling should include responses to types of biochar that are currently less well studied, such as biochar resulting from fast pyrolysis<sup>5</sup> of herbaceous feedstocks, and processed biochar products (such as mineral-enhanced or other functionalized products<sup>6</sup>). Improved mechanistic understanding of how biochar impacts soils and plants could also inform ongoing efforts to produce specialized biochar types that are well-suited for specific end uses such as co-composting or mine land reclamation. Together with information on markets for specific biochar end uses, such information could inform development of production systems for specialized biochars.

In addition to impacts on plant growth and yield, biochar can influence ecosystem services, and filling these knowledge gaps could help build a foundation for policy efforts. Specifically, we need better understanding of how widespread adoption of biochar systems will impact the ecosystems in which harvest and application occur. In the case of forest biomass, sustainable biochar production must dovetail with land management goals to achieve sustainable harvest of forest biomass. Though application of biochar has the potential to improve the resilience of forest and agricultural ecosystems to climate change and other stressors, there is still a great deal to learn about the particular biochar-soil-crop (or forest) scenarios in which biochar is most impactful.

## Impacts on Climate

It is important to gain a more complete understanding of the biophysical processes affecting greenhouse gas (GHG) emissions of biochar systems in various production and application scenarios. This information will lay the groundwork enabling biochar applicators to access C markets. An improved understanding will also inform policies aimed at encouraging biochar production and use.

In the 2007 IPCC 4th Assessment Report, approximately 90% of the total technical GHG mitigation potential in agriculture is attributed to C sequestration [41] yet observed C sequestration rates from particular management practices have varied greatly primarily due to differences in soil type, topography, biomass material, climate, and management practices [30]. Given this, it would be reasonable to expect significant variation in the C sequestration resulting from different biochar applications to diverse cropping systems. We need better understanding of the long-term effects of different biochar types on changes in soil organic C stocks and GHG emissions across different climates, soil types and management systems. This also includes an understanding of the biochar-microbial interactions that lead to changes in the rates at which biochar C is returned to the atmosphere, and the effect of these changes on soil organic C stocks (the “priming effect”). While many, predominantly short-term studies have been carried out over the past decade or two, there is a need for more long-term research.

5 A form of pyrolysis characterized by the rapid heating of biomass (heating rates of over 300 °C per minute). See Chapter 11.

6 Functionalized biochar has been modified with chemical agents or additives (functionalizing agents) that improve its performance for a particular use. For example, iron oxide is added as a slurry during quenching to improve phosphorus removal, kaolin clay may be added to improve binding with herbicides. (Personal communication, Jim Dooley)



**Figure 2.5.** Integrating biochar production with commercial compost facilities, like the one pictured, offers promise. Compost facilities have a ready source of woody materials (compost overs) and co-composting with biochar can produce a high-value soil amendment. (Photo: Doug Collins)

A full understanding of the climate benefits resulting from production and application of a particular biochar—necessary prior to the development of policy incentives—results not only from the climate impacts once applied to soils, but also from the GHGs emitted (or avoided) during production. Thus, rigorous measurements of GHG emissions are needed for biomass harvesting and transportation, for biochar production, transportation, and application, and for the soil system to which biochar is ultimately applied. These emissions then need to be compared with those emissions associated with the other potential fates of the biomass to determine the net climate benefit for a given production and application scenario.

## Impacts on Composting Operations

Industrial composting operations have a ready supply of woody material (compost overs) that are widely considered a waste byproduct, and which could potentially be used as a biochar feedstock (Figure 2.5). Further, there are indications that biochar, when introduced at the beginning of the composting process, can reduce emissions of volatile organic compounds<sup>7</sup> (VOCs), ammonia, and sulfur compounds during composting [14]. The impact on GHG emissions varies substantially with most evidence pointing to a decrease in GHG emissions during composting of manures [22, 51].

A key benefit of co-composted biochar is that the final product seems, in some cases, to be a better soil amendment than either compost or biochar alone as demonstrated through evaluation of crop growth and yields in potted-plant experiments and field trials [1, 14, 33, 34, 42, 46]. However, as with un-composted biochar, results vary.

For all these reasons, integration of biochar with composting operations seems promising. However, several questions specific to biochar's use in these operations remain including the characteristics and functional properties of biochar that alter compost emissions, how the compost process impacts biochar properties, and the biophysical processes by which co-composted biochars can benefit plants when applied to soils.

## ECONOMIC

Economic viability remains a significant challenge for biochar systems [9, 25, 38, 40, 47]. Critical factors affecting economic viability include: 1) costs associated with feedstock acquisition, capital, operations, and transportation of feedstocks and products, and 2) the income streams associated with energy and biochar products, climate offsets, and renewable energy subsidies. Currently, conversion of biomass to bioenergy is more profitable and this situation even extends to the relative economics of fast-pyrolysis

<sup>7</sup> Some of the VOCs produced during composting are problematic. Sulfur-containing VOCs are the sources of unpleasant odors that can be associated with compost. Other chemically reactive VOCs affect the formation of ozone and particulate matter, while others are listed as air toxics by the EPA, and directly impact human health.

systems, which generate more bioenergy and less biochar than slow-pyrolysis systems [7]. The situation is reversed, however, when the biochar and bioenergy systems are compared based on their potential to mitigate climate change [50]. In their analysis, Shackley et al. [38] concluded that the economic disadvantage of biochar systems relative to bioenergy systems will remain until government policies that appropriately value and monetize the generally higher climate benefits of biochar are successfully implemented.

The key issues affecting economic viability can be broadly categorized as being related to either further reducing the cost of production or enhancing market value.

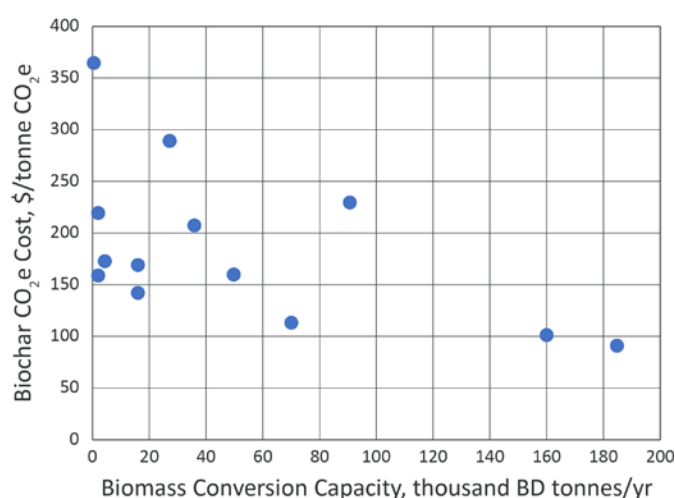
## Cost of Production

Feedstock costs (which, in the case of forest biomass, are associated primarily with biomass harvest and transport, but also include on-site storage) are of critical importance for economic viability [38]. High feedstock procurement costs will critically decrease the feasibility of biochar production operations. Specific thresholds for feedstock costs vary depending on the specifics of a biochar production system, but several studies suggest a range of about \$70 to \$90 per tonne (\$63 to \$82 per ton) for agricultural and forestry residues in the absence of subsidies [7, 13, 37, 38]. As a proportion of overall biochar production expenses, feedstock costs range from about 40% to 75% depending on the scale of production [38]. There is a need to optimize operational logistics to bring down feedstock costs where possible.

Labor, logistics, and capital make biochar production costly at scales up to about 100,000 BD tons per year of feedstock. Thermal equipment and emissions control are expensive (\$1 million or more per dry ton per hour fuel input) [26]. Availability of low-cost biochar production technologies in the 30,000 to 100,000 BD ton per year range is still lacking and operational costs associated with these systems are prohibitive, making it difficult to increase biochar production at or near the forest. In general, the smaller the scale of production, the more labor intensive it is. With the current relative costs of labor and capital in the U.S. the smaller scales are, almost by definition, more costly per unit output. As production scale increases, the corresponding increase in output is achieved by automation with a concomitant increase in productivity per worker.

An idea of the impact of production scale on economics of biochar-generated C offsets (i.e., dollars per tonne carbon dioxide equivalents [CO<sub>2</sub>e]) is given in Figure 2.6. At the largest production scale typical of a centralized

facility, cost is about \$100 per tonne (\$91 per ton) CO<sub>2</sub>e. As the scale of production decreases, the cost increases to a general range of about \$150 to \$225 per tonne (\$136 to \$204 per ton) CO<sub>2</sub>e at the smaller scales (with one 500 tonnes [551 tons] biomass per year system yielding \$365 per tonne [\$331 per ton] CO<sub>2</sub>e). Missing from this analysis are economic data for the smallest production scale (less than 500 tonnes biomass per year), which involves labor-intensive manual operations, short transportation distances (typically on-site forest thinning or farm operations) and small, inexpensive, low-tech units (flame-cap kilns). Production at this scale would likely tackle the biomass that is not readily accessible by the mechanized operations which characterize the larger-scale operations. Also missing from the analysis are biochar systems that monetize energy released as heat during production (combined heat and biochar or CHAB). These are systems used to power small buildings, schools, or light industry and would be expected to have better economic performance than the low-tech kilns.



**Figure 2.6.** Changes in the cost of biochar-generated offsets (\$ per tonne CO<sub>2</sub>e) with the scale of production (BD tonnes biomass converted per year). Economic data for biochar production selected from Shackley et al. ([38], Table 29.3) were combined with the following assumed data: Feedstock cost \$70 per BD tonne; Biochar yield 0.33 tonnes per BD tonne feedstock; Feedstock C content 50%, Biochar C content 80%, Biochar offset, 4.04 tonnes CO<sub>2</sub>e per BD tonne biochar C. Biochar offset is based on recent data for Washington State by Amonette [4].

As with other emerging industries, commercialization of biochar businesses presents significant risk to entrepreneurs, limiting the pace of commercialization. The type of large-scale research and development projects that helped commercialize biomass to jet fuel or mass-timber construction have not yet occurred in the biochar space. Instead, existing biomass conversion systems developed for other purposes are modified for use as biochar production systems and may not yield optimal results with respect to maximizing economic or C-offset value.



Similarly, technical assistance programs to support entrepreneurs are also relatively lacking across all scales of biochar development. Though strong technical expertise exists, it is not widely available through targeted technical assistance programs in the nascent biochar industry. In part, this is a matter of lack of sufficient funding, both to connect individual entrepreneurs with the technical experts and to nurture the development of new concepts.

At each of the three scales considered in this report—hand fed kilns and pyrolyzers, moderate-scale on-site pyrolyzers and gasifiers, and central facility gasifiers and boilers—technoeconomic analyses can provide critical insights. These types of analyses can assist with determining locations best suited for biochar production facilities, and in better understanding tradeoffs in operation of facilities to produce more or less biochar compared to energy and other co-products.

Because the industry is still emerging, developers of centralized facilities are challenged to convince investors that markets are sufficient to support the investment in new large facilities. While helpful, current markets and environmental credits (e.g., C credits, subsidies) do not generate sufficient cash flow to fully offset the financial risk for these centralized facilities.

## Market Value

Because the cost of transportation is high relative to product value, biochar markets are currently regional. Thus, access to biochar product markets within a reasonable distance (i.e., less than 100 miles) is important for a successful business operation (Figure 2.7). Nevertheless, as demonstrated by the development of international markets for use of white-wood pellets and torrefied-wood<sup>8</sup> fuel in renewable-electricity generation, policy incentives that increase market value could substantially enlarge the geographical reach of the biochar industry.

Agriculture is an important potential market for biochar due to the quantities that could be absorbed. Because of the current regional footprint of the biochar industry, building the agricultural market requires developing solutions to local agronomic problems using locally available biochar resources. Once solutions are developed, the challenge becomes one of encouraging their adoption. This is because most agricultural producers who grow commodity crops on slim margins are slow



**Figure 2.7.** Biochar in supersacks ready for transport to regional markets. (Photo: Karl Strahl)

to adopt new practices, needing several years of demonstration on large field plots before making a change. For these producers, development of a partial budget analysis approach for key cropping systems (e.g., wheat) in the Western region, similar to that developed by the Soil Health Institute for the Midwest region where corn and soybeans are the dominant crop [39], may help speed adoption. Specialty and niche producers who practice organic and regenerative practices or grow high-value crops such as vegetables, orchard fruits, grapes, berries, and cannabis have been more willing to try biochar. Further information is needed to identify other situations in which producers and other end users are willing to pay for biochar when it helps solve specific problems. Despite this optimism, a number of economic analyses have indicated that without policy incentives, biochar application is unlikely to occur within low-margin commodity crops that are grown on many more acres [15, 36].

Another potential market for biochar involves environmental remediation. In addition to research demonstrating promising applications, market development in this area requires more landscape architects and engineers to write specifications and best management practices for the use of biochar to encourage the inclusion of biochar in bid specifications and the purchase of biochar by the contractors awarded the work. This is a lengthy process, that typical takes three to five years from the writing of project specifications to the performance of the work.

Embryonic markets [27, 44] include use of biochar as a livestock feed supplement [24, 49], as a filler in composites [23, 32], and as a substitute for asphalt in

<sup>8</sup> Torrefied wood is produced by torrefaction, a thermal pretreatment process to pretreat biomass in the temperature range of 200–300 °C under an inert atmosphere. (<https://www.sciencedirect.com/topics/chemistry/torrefaction>)

road building [45] and for aggregate in concrete [2, 10]. These applications will face regulatory hurdles that are best overcome by research, development, and performance testing of candidate products.

Consistency of quality from a single producer is vitally important to meeting customer expectations and supporting viable biochar pricing [16, 48]. A U.S. survey of 61 biochar producers and 58 biochar users conducted in 2018 found that both producers and users “see the need for more attention to be paid to the characteristics and quality of the end product.” [16]

Substantial progress has been made to develop widely accepted product quality standards but further work is needed to align diverse systems [16]. International Biochar Initiative (IBI) Standard 2.2 categorizes biochars by C content in three classes of biochars >10%, >30%, and >60% C. A system of classifying biochars for use in soil and on-line tools for general use are also available [8]. However, in the U.S., the Association of American Plant Food Control Officials (AAPFCO) requires a 60% minimum C content for a product to be labeled as biochar. This may cause problems as several moderate-scale production methods produce biochar with a C content less than 60%. Meanwhile, the USDA defines biochar used as a soil amendment as having a threshold of 25% C. The American Society of Agricultural and Biological Engineers is another organization that might support the development of standards that align with those available from the International Organization for Standardization (ISO). Engagement with the ISO Technical Committee having responsibility for solid biofuels (*ISO TC 238*) is needed to help with the unique aspects of biochar technology.

Finally, the benefits of biochar are still not widely recognized by many potential soil-amendment customers (e.g., public agencies, parks, golf courses, commercial gardens, organic farmers, and sustainable agricultural producers). Once informed of the benefits, these potential biochar customers will need information on product availability, appropriate packaging (supersacks and bulk), and fair pricing. The 2018 survey of U.S. biochar producers and users [16] pointed to the importance of customer and public education on biochar as well as the need to scientifically validate claims made regarding the benefits

of biochar. Publication of well-executed techno-economic and life cycle assessments that quantify the potentials for cost reduction and C sequestration that would accrue from greater demand for biochar would help with this effort.

## Regulatory

Both stationary and mobile biochar production facilities need to comply with all applicable regulatory requirements, and sites may require air permits, stormwater permits, waste discharge permits, solid waste permits, conditional use permits, and other environmental review. The specific regulatory requirements will depend on the size and location of the facility, technology operational characteristics, feedstock composition, origin, and designation, site land use zoning, regulating jurisdiction, and nearby environmental conditions.

While an in-depth analysis of all permitting issues was beyond the scope of the workshop, the cost and complexity of air emissions permitting can be an important barrier to more widespread adoption of biochar production. States and tribal agencies have primacy for implementing the U.S. Clean Air Act, which provides a federal basis for air quality permitting.<sup>9</sup> In some states, local air agencies have been established over smaller areas. Different tribal, state, and local agencies have different approaches to permitting biochar units, arising from the multiple and emerging technologies, variation in air quality issues, differences in state regulations, and other factors.

Despite this variability, a few general observations are possible. First, permitting processes depend on knowledge about emissions of criteria air pollutants<sup>10</sup> and toxic air pollutants<sup>11</sup>, and this process is hampered by a lack of data for many biochar production technologies. The fact that emissions can be quite variable, depending on feedstock type, moisture content, and equipment parameters, also adds complexity.

Second, those who are exploring the use of biochar production units to replace open burns in forestry (Figure 2.8) and agriculture will generally find that despite the air quality benefit that biochar provides (e.g. [28]), the applicable regulatory process is substans

9 The EPA is responsible for air emissions permitting on tribal land for tribes that have not developed federally recognized permitting programs. To date, although some tribes have local environmental requirements, few tribes have approved permitting programs.

10 Criteria air pollutants are air pollutants for which the EPA has established National Ambient Air Quality Standards (NAAQS), including particulate matter (PM), photochemical oxidants (including ozone, O<sub>3</sub>), nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), sulfur oxides, and lead (Pb). Volatile organic compounds (VOC), C-containing compounds involved in O<sub>3</sub> formation, are also regulated as criteria air pollutants.

11 Toxic air pollutants, also called hazardous air pollutants, are those pollutants that cause or may cause cancer, reproductive effects, birth defects or other serious health effects, or adverse environmental and ecological effects.

tially more complex, costly, and time consuming than the permitting process for open burns. For example, in Washington State, the Department of Natural Resources provides regulatory oversight for pile or understory burning in forestry contexts. The primary aim of this oversight is to avoid violating the NAAQS<sup>12</sup>. In practice, the amount of burning allowed is based on the weather forecast and the distance upwind from communities, with a focus on keeping smoke and small-diameter particulate matter (PM<sub>2.5</sub>) away from communities, and not worsening haze in areas that are protected by the Class I Regional Haze Rule. In contrast, those seeking to operate biochar production systems will generally need to obtain an air emissions permit from the appropriate state, local, or tribal authority, and the process is likely to require addressing both toxic air pollutants and criteria pollutants.



**Figure 2.8.** This slash pile burn was part of a study to examine the heat pulse of burning piles into soils of different moisture contents (spring and fall burning) and textures (silt loam to gravelly sandy loam). This photo was taken on the Lubrecht Experimental Forest in Montana. (Photo: USDA Forest Service)

Third, portable or temporary biochar production systems represent a particularly difficult issue for most local air quality agencies. Mobile units are also often smaller-scale operations, for whom the permitting costs can be prohibitively complex, time consuming, and expensive. And in situations where mobile facilities are used primarily to produce biochar from residues in place of open burns, permitting can serve as an obstacle to improvements in air quality, counter to its original intent. However, although there

are some allowances for certain limited temporary operations, the existing regulatory structure tends to require that these units have permits. There are also concerns relating to the ability to know how often they will move, what areas they will operate in, and how regulators will be able to access them for inspections. Obtaining land use approval at multiple locations may also be a challenge. Addressing these issues may require long-term policy work to develop regulatory structures that are appropriate to their scale and use, while also protecting air quality for the communities near their operation.

## Financial

Financial investors in energy markets and C-trading markets have not been widely educated about the potential of the market from biochar. Painting a clear picture of the potential size of this market, creating some advocates within government agencies and trade associations, and engaging the advocates with large-scale financial investors will be key for successful growth of the biochar industry.

Progress in this area will be path specific. To date, only one life cycle assessment for C credit generation has been developed or approved for any biochar system in California. Potentially each production facility, feedstock supply, and biochar use could require registration, though with costs for initial registration estimated at \$100K per path, this could be prohibitive for all but the largest facilities. Thus, focusing on large-volume pathways makes strong initial sense. There could also be a very strong role for trade associations (e.g., U.S. Biochar Initiative, USBI) rather than individual companies or individual projects to get the initial registrations. With the experience and education gained from these large-volume pathway registrations, the expectation is that, over time, registration costs will decrease and smaller-volume pathways will become easier to register. Enlisting well-respected third parties and scientists whose work has informed other pathways used in Argonne National Laboratory's GREET<sup>®</sup> life cycle assessment model [6] may be of substantial help in identifying the best pathways and ensuring the foundations on which they are built are sound.

Additional opportunities (and uncertainties) are associated with the potential impact of biochar on crop insurance and farmer loans, with enormous implications for farmers. If biochar can be shown to consistently reduce production risks, one could

12 National Ambient Air Quality Standards



imagine that those producers using biochar could have discounted crop insurance rates, which could spur adoption. On the other hand, one can envision that by lowering production risks, biochar could also make these same producers ineligible for other crop protection programs, thus hindering adoption. Another uncertainty relates to the conditions under which banks will lend to producers who use biochar. As with crop insurance, depending on their assessment of the potential risks, banks could charge different rates (higher or lower) for producers who use biochar. Field research demonstrating the benefits of biochar use, coupled with education of lenders and growers, could lead to lower lending rates thereby facilitating adoption.

## PUBLIC ENGAGEMENT AND SUPPORT

Public engagement and support is critical to advance the biochar industry. One form of engagement is by those directly involved in biochar systems, including public and private land managers, contractors, potential end users, and technical service providers. These individuals form a potential group who could work towards supportive biochar policy and could also benefit from improved support. 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.

Another important group to engage is the general public. Unlike processes such as composting, biochar and its production are not well known or understood. Education of the general public thus provides an important opportunity for individual consumer use at the homeowner level. An informed public could also provide an important voice that could advocate with policy makers and regulators to make the needed changes for development of biochar systems.

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## CHAPTER 3:

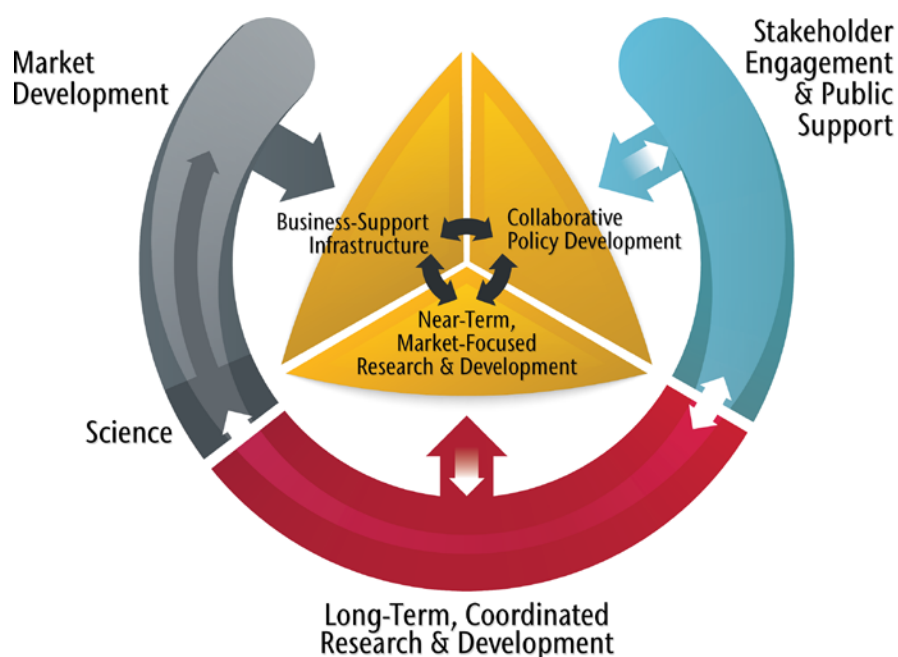
# Recommended Funding Strategies

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## OVERALL STRATEGY

### Major Priority Areas

To address the challenges and opportunities identified in Chapter 2 and maximize the benefits that biochar can provide to communities across the region, nation, and globe, we recommend that private, governmental, and philanthropic investments be directed towards four major areas. First, a **long-term coordinated program of research** is needed to help resolve the remaining scientific and engineering knowledge gaps with respect to biochar production, use, and climate impact. Transfer of this knowledge to practice, however, will require equally important efforts to 2) conduct **near-term, market-focused research** on issues related to regional implementation and expansion of biochar markets, 3) strengthen the **infrastructure to support business** by providing financial tools and incentives, a trained workforce, and an engaged customer base, and 4) collaboratively develop **environmental regulations and ecosystem-service-pricing policies** aligned with biochar technology. Success in all four of these priority areas will require **engagement with the public**, both to educate them with respect to the



**Figure 3.1.** 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)

many benefits of biochar technology and to listen to their suggestions and concerns. Based on this engagement, the research, economic, and policy agendas we propose here will need to be continuously updated to ensure the broadest public support for the adoption of sustainable and climate-friendly biochar technology.

### Roadmap

The relationship between these four priority areas is illustrated in Figure 3.1. The **long-term (decades-scale) coordinated research program** provides the scientific and engineering foundation for biochar technology. As currently envisioned, this



program could be national or international in scope and would involve coordination among a series of regional sites devoted to understanding the science and improving the climate-, energy-, labor-, and capital-efficiency of biochar technology. An advisory council composed of representatives of various stakeholder groups would help guide the program. Novel engineering approaches would be developed and tested. An improved understanding of the biophysical processes involved in biochar production and use would be developed. The fundamental knowledge generated would be used to improve models of biochar reactor designs and plant response to biochar amendments, to develop life cycle assessments of net climate impact, and to construct techno-economic pathways and macro-economic scenarios for adoption of biochar technology. A knowledge consolidation and extension effort would ensure that the new information generated by the program would be readily available to biochar technology practitioners, government agencies, and the general public.

This knowledge developed in the more fundamentally focused long-term research program would also help guide **near-term (one to three year) research efforts aimed at overcoming barriers to market development**. These efforts would 1) develop protocols and specifications to ensure product consistency and appropriate use of biochar, 2) construct and apply

algorithms to assess the market value of ecosystem services provided by the application of biochar technology, and 3) measure environmental emissions factors associated with biochar production to help refine regulatory approaches. A fourth major category of near-term research would largely focus on regional market development and include pilot-scale demonstrations of biochar technology. Specific markets would include prescriptive applications of biochar to agronomic, silvicultural, horticultural, range management (Figure 3.2), and livestock systems to solve specific problems. Others would include applications of biochar technology for fire-hazard reduction, land reclamation and restoration, co-composting of municipal and agricultural waste, environmental filtration of contaminants from waterways, and the development of new high-value C-based materials.

The results of the near-term research efforts would inform, enable, and be responsive to the other two major funding priority areas shown in the center triangle of Figure 3.1. Funding to **develop and strengthen the support infrastructure for business** would focus on three areas: 1) direct assistance to businesses to develop partnerships and to provide planning tools as well as technical, regulatory, and financial aid, 2) training of a diverse workforce, and 3) engagement with potential customers (including retail nurseries and garden centers as well as potential biochar end users) through marketing research and








**Figure 3.2.** Field plots to measure the influence of juniper biochar on the establishment of bunchgrass in rangeland are installed at Six Shooter Ranch in Mitchell, Oregon. (Photo: Marcus Kauffman)

the subsequent development of customer awareness campaigns. Implementation of business-support infrastructure would involve strengthening existing biochar industry trade organizations such as the [International Biochar Initiative](#) and the [United States Biochar Initiative](#), as well as potentially endowing an entirely new organization (analogous in many ways to the [United States Endowment for Forestry and Communities](#)) to promote biochar-based community development activities.

Funding for the fourth major priority, **collaborative development of policy related to biochar technology**, would focus on development of 1) robust pricing mechanisms to pay biochar practitioners for the ecosystem services they provide, and 2) appropriate environmental permitting instruments related to biochar production. As indicated in Figure 3.1, a key aspect of this funding effort would be the engagement and formation of partnerships with a wide range of potential stakeholders as well as the general public to develop specific policies.

In the remainder of this chapter, we provide further details regarding the four major investment priorities recommended by the workshop. Some of these concepts are best funded by philanthropic organizations, others by national, state, or local governmental agencies, and still others by private capital. To identify our assessment of likely funding entities we have provided one or more icons at the start of each concept description, with the first icon listed being the most applicable to a specific concept. These are:

-  Philanthropic organizations
-  National governmental agencies
-  State/Provincial governmental agencies
-  Local governmental agencies
-  Private capital

## LONG-TERM MULTI-SITE COORDINATED RESEARCH PROGRAM



### Rationale

Although natural wildfires have generated charcoal for about 420 million years [26] and humans have been making charcoal from biomass for tens of millennia, either intentionally [3] or inadvertently [11], the concept that biochar could be produced deliberately for use as a tool to mitigate climate change while increasing biomass productivity has been around for less than three decades [12, 14-16, 27, 29, see supplementary note in 33]. The past two decades has seen an explosion in research devoted to this topic [34], but much of the research is of a short-term nature and significant knowledge gaps remain. If research were to continue to proceed “organically,” several decades might pass before these gaps were closed given the complexity of the field (multiple sources of biomass, methods of biochar production, soil types, and potential plant systems to consider). Given the urgency of climate change and the potential contribution that biochar can make to its mitigation, the consensus of the workshop is that the organic approach is a luxury we cannot afford. Consequently, **we recommend that a decades-long coordinated multi-site research and development program implemented at a national (or even international) scale would be the fastest way to close the fundamental scientific and engineering knowledge gaps** and thereby provide the knowledge needed to address the key economic and policy challenges discussed in Chapter 2.

First, we discuss three broad research areas to be addressed by the proposed program: engineering, biophysical processes, and model development. We then describe a knowledge consolidation and extension effort to ensure that the information developed by the research effort is shared as widely and efficiently as possible. Finally, we describe some initial thoughts about program structure and governance.

### Research Topics

#### Engineering

Two of the key challenges addressed by engineering are lowering the cost and improving the overall climate impact of the biomass-to-biochar conversion process.

Lower cost will be achieved 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. The first three of these activities lend themselves well to vertical integration, that is, the design of equipment to maximize biochar/bioenergy production efficiency from biomass harvest through post-production processing of biochar. An example of how this might be done with woody biomass feedstocks is given in the sidebar “*Designing Sustainable Biochar Systems*”.

Application of biochar is another area where engineering can lower costs while ensuring proper and safe placement of the biochar. The optimum methods of application will differ for agronomic, horticultural, forested, and grassland sites (Figure 3.3). Although the nature of the application site will largely dictate the design of application equipment, the ability to accommodate biochars prepared from different biomass sources by different methods and to integrate with existing agricultural and forestry equipment will likely be important secondary design considerations.

To improve the climate impact, engineering will largely focus on optimizing the production process to increase C efficiency (the fraction of biomass C that ends up in the biochar) and decrease the amount of CH<sub>4</sub> and soot released to the atmosphere. The quality of the



**Figure 3.3.** Broadcast application of mixed-wood biochar on the Armstrong Memorial Research and Demonstration Farm near Lewis, Iowa. (Photo: David Laird)

biochar produced matters also—the more stable the biochar is to oxidation once in soil, the greater the C sequestration potential and better the climate impact. Engineering is needed to develop biochar production equipment that optimize these design criteria for different scales of operation—ranging from the landscape scale encountered with small landholdings and farms, through moderate-scale production at forest landings, to large-scale production at centralized facilities. This work will require close coordination between development of theoretical pyrolysis reactor designs and the construction and testing of pilot-scale pyrolysis reactors to validate these designs.

## Designing Sustainable Biochar Systems

In 1992, the Hannover Principles for sustainable design were first published [17]. A full example of the application of these principles is given as Scenario 1 in Chapter 5. The goals are to approach the minimum theoretical energy consumption and maximize the C content of the biochar while closing the materials and energy balance for the entire biomass to biochar system.

Scenario 1 includes the following steps: 1) gather intact biomass and transport it by baling or bundling to the production site; 2) for conversion to biochar, crush the biomass into ¼-inch diameter scrim using rollers followed by cross-shearing; use screening to remove oversized pieces (for re-crushing) and fines containing

soil (for mulch); 3) locate the biochar production system at the forest landing and only move it, if at all, every few weeks to months; 4) dry the sheared scrim using exhaust gases from the pyrolyzer and condense the water vapor (after filtration to remove terpenes as a product stream) for subsequent use to quench the biochar; 5) design the pyrolyzer to run continuously at a feed rate of 1-5 tons per hour, maximize biochar-C efficiency, and to operate across a range of temperatures and feedstock sizes so that a variety of tailored biochar products can be made; 6) incorporate the ability to apply functionalizing agents to the feedstock, before pyrolysis, or to the biochar during the quench process; 7) when cool, package

the biochar in supersacks for shipment to a central warehouse for final processing and distribution to customers.

Another example of these principles applied is the Biomass Utilization Campus (BUC) described in Chapter 6. Briefly, a BUC is an integrated processing facility to convert solid wood and residues to a variety of value-added products including biochar. It allows for multiple industries to share the cost of harvesting and transportation. Dimensional lumber, round timbers, post/pole, fiber logs, kiln dried firewood, beauty bark and mulches can be produced while residues from these processes can be converted to energy and biochar, all in a centralized facility. ■



## Biophysical Processes

The primary focus of research into the biophysical processes that operate in managed and natural ecosystems will be to increase the understanding of the various climate-related and economic impacts that biochar has on the diverse systems in which it may be applied to the degree required to ensure successful and widespread deployment. Potential impacts to be investigated include changes in crop yield, quality, and nutrient density, native soil-C stocks (See sidebar in Chapter 2: “*Biochar’s Impact on Native Soil Carbon Stocks*”), disease pressure, greenhouse gas (GHG) fluxes, compost production efficiency, fertilizer and herbicide use efficiency, and resilience of natural ecosystems. While agricultural systems, particularly in the tropics, have been studied the most, few data exist concerning these potential impacts on horticultural, silvicultural, and grassland systems and on agricultural systems in temperate climate zones. A wide variety of measurements are needed from controlled plot trials to inform and constrain models that can predict the climate-related, economic, and ecosystem service impacts of biochar amendments in these systems.

The types of biomass feedstocks (e.g., wood, straw, and manure) and biochar production methods used have an impact on the intrinsic properties of biochar, including stability of the C, ash type and content, acid/base character, porosity, and water holding capacity. While a fair amount of knowledge exists regarding these impacts, further refinement is needed to improve the efficiency of production and increase the climate benefit of the biochar.

In addition to field applications, biochar is added to municipal and agricultural composting operations where it may impact the time required (and hence cost of production) to finish the compost as well as the total quantities of GHGs emitted during the process, and potentially improve the value of the end compost product. The composting process can also impact the properties of the biochar. More information is needed about these co-composting impacts and how they change with the type of biochar, compost feedstock, and method of composting. We propose that research specifically focused on municipal and agricultural co-composting operations be conducted to answer these questions.

## Model Development

Predictive computer-based models are essential tools for consolidating knowledge in a form that allows it to be used to solve problems and inform decision makers. As an integral part of this program, we propose to

develop the next generation of fundamental pyrolysis models to assist in the design, engineering, and testing of the reactors that make biochar at different scales. Models to optimize the logistical factors across the biomass-to-biochar supply chain are also needed. Just as important, however, will be the development of a range of powerful response models that build on the data generated in the engineering and biophysical processes areas to predict the impacts of biochar technology.

Examples include:

- productivity and yield responses of plants to biochar applications,
- impact of biochar on agroecosystem resilience including building soil organic matter, cycling of water and nutrients and fate and transport of agrochemicals and fertilizers,
- integrated life cycle assessments of the climate benefits of various implementations of biochar technology,
- techno-economic assessments of the most favorable pathways to large-scale implementation of biochar technology,
- macro-economic scenarios of the overall impact of the integration of biochar technology into the economic mainstream and, ultimately,
- integration of the productivity response, life cycle assessment, and economic models with the general circulation models that predict global climate change, thus allowing a clearer assessment of the potential impacts that biochar technology can have under different climate-change scenarios as well as the impact of climate change on the biomass-to-biochar supply chain.

## Knowledge Consolidation and Extension

To have the desired impact, the results of this research program need to be archived, consolidated, and communicated to other researchers, biochar practitioners, stakeholders, and the general public. Conversely, communication from these same entities to the research program is needed to share concerns, help interpret results and stimulate new ideas that can guide further research. To accomplish these two functions, we propose a major three-part effort:

- Establish an online information clearinghouse (in conjunction with the biochar trade organizations) that would contain electronic versions of the

experimental data, technical reports and scientific publications generated by the program, together with relevant publicly available reports from other organizations and individuals active in biochar technology research and development. This clearinghouse would provide a focal point for discussion and information exchange by interested parties from around the world.

- Compile the scientific knowledge developed by the program together with that from other organizations, businesses, and individuals active in biochar technology research and development into a series of topical reports as well as documents describing best management practices. These documents would be freely available to biochar practitioners and other interested parties, thereby helping to promote the best possible climate-mitigation and economic outcomes from the production and use of biochar.
- Set up an interactive outreach effort, involving workshops and webinars, online curricula, and field days at biochar production facilities and test plots to communicate directly with the larger community interested in biochar technology. This effort would stimulate education and discussion, sharing of concerns, and the formation of new concepts, thus further strengthening the research program and amplifying its impact.

## Program Structure

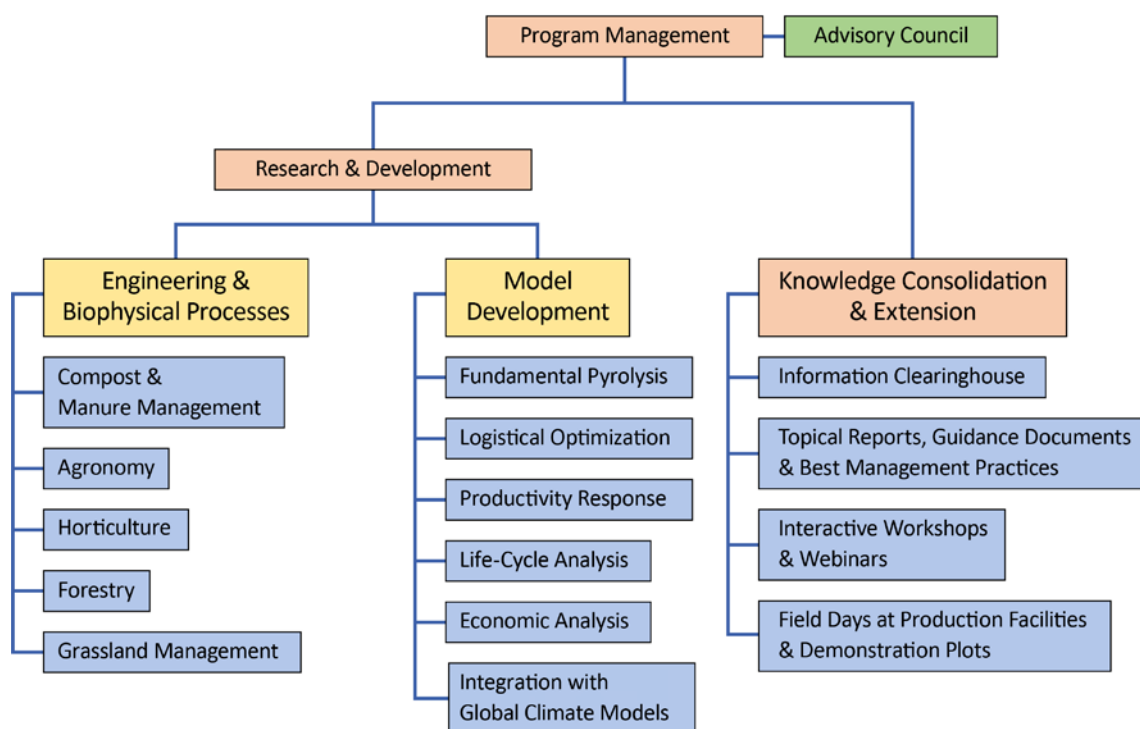
We propose that the long-term research and development program would be led by a management team responsible for coordinating the three major types of activities: engineering and biophysical process research, model development, and knowledge consolidation and extension (Figure 3.4). The team would meet regularly with a moderately sized (24-36 members) advisory council consisting of representatives from the biochar technology field (50%), scientific experts in broader topical areas relevant to the research (25%), and a cross section of potential stakeholders (25%). During these meetings, program progress would be shared, and input related to program goals, research projects, and outreach activities sought from the council members.

The topical areas for the *Modeling Development* and the *Knowledge Consolidation and Extension* activities are listed in Figure 3.4 as described earlier. We propose to organize the *Engineering and Biophysical Processes* activities into five topical groups (Figure 3.4 and 3.5). The first group would focus on the use of biochar in a range of composting operations (municipal green

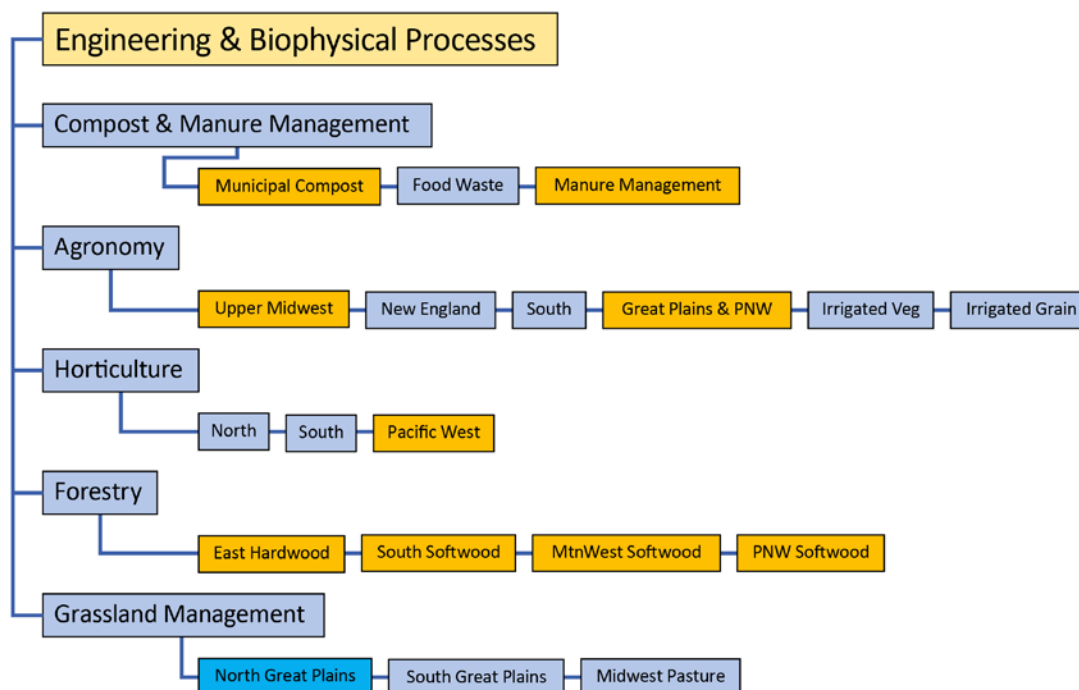
waste, food waste, biosolids/animal manures), and on the production of biochar using municipal green waste, biosolids, and animal manures as feedstocks. Engineering for biochar production, energy, and chemicals would be conducted at two locations, one focused on municipal solid waste facilities using a variety of feedstocks (recovered wood, green waste, biosolids) and one focused on using animal manures from large-scale animal production facilities (e.g., dairy farms, feedlots, poultry production facilities) as feedstock.

The remaining topical groups would focus on geographically relevant research questions related to the production and use of biochar in agronomy, horticulture, forestry, and grassland management (Figure 3.5). The exact number of sites would need to be determined (see [2] for another example), but nominally, research would be distributed among six sites for agronomy, three sites for horticulture, four sites for forestry, and three sites for grassland management. Two of the agronomy sites, one of the horticulture sites, and all the forestry sites would include biochar production and the associated engineering development activity. In addition to biochar production, the engineering activity at the four forestry sites would include a strong focus on biomass handling and biochar application technology, as these would be expected to differ significantly among the sites. The engineering development activity at the grassland management sites would focus solely on biochar application methods. Taken as a whole, therefore, the program would produce biochar from wood, straw/stover, municipal green waste, orchard/vineyard prunings, biosolids, and animal manure, using a variety of production methods, and it would have the capability of co-composting any of these biochars.

The biochar response research conducted under the agronomy, horticulture, forestry, and grassland management areas would likely consist of 1) a core set of mechanistically focused experiments applied across all sites that would allow comparisons of the relative effects of soil, climate, and plant type to application of a common project-wide biochar at a standard set of application rates, and 2) a larger set of site-directed experiments that would focus on application of locally produced biochars and testing of different application methods, watering regimes, and fertilization strategies. Within each topical research area, testing using a common plant type (when practical) with the common biochar would further improve assessment of soil and climate effects on observed responses to biochar amendments. Results from both types of experiments would be used to drive and validate the model development efforts.



**Figure 3.4.** Proposed long-term coordinated research and development program structure showing major groupings of activities.



**Figure 3.5.** Proposed topical/geographic sites for Engineering & Biophysical Processes efforts in long-term coordinated research and development program. All sites would conduct research on impacts of biochar amendments to soils. Orange-colored sites include biochar production and engineering capabilities; the brilliant blue site includes engineering capability only for biochar application technology.



## Program Sponsorship

At face value, the geographic complexity and long-term nature of this proposed research and development program would require a substantial level of funding, possibly on the order of \$150-200 million per year for the first decade [2]. Smaller levels of funding to maintain the long-term experiments would be envisioned for the decades to follow. Significant cost savings could be achieved by leveraging existing USDA agronomic and forestry research infrastructure, and developing collaborations with universities, state agencies, private foundations, farm organizations, environmental groups, and private venture capital. Formation of a formal consortium for this purpose might be the best path forward.

An international version of this program with a proportionally larger geographic footprint can also be envisioned, with support to come from a variety of national and international funding sources. In this instance, the model provided by the Consortium of International Agricultural Research Centers ([CGIAR](#)) is a good example that also leverages the available existing research infrastructure.

Whether national or international in scope, we think that the promise of biochar technology to address climate change, food security, and the need to stabilize/revitalize rural communities is most readily met by a coordinated program like the one we have described here.

## NEAR-TERM MARKET-FOCUSED RESEARCH AND DEVELOPMENT



Bringing sustainable biochar to market requires near-term actions such as the development of **characterization and labeling protocols** as well as **guidelines for successful application and use**. It also requires market-focused research and development that, in some instances, builds on data collected during the long-term coordinated research program. Critical needs include 1) measurements of **environmental emissions factors** for biochar production systems and development of algorithms suitable for regulatory purposes, 2) development of scientifically defensible algorithms to **estimate the contribution and market value of biochar technology to ecosystem services** including climate change mitigation, soil health, air quality and human health, and water storage. In addition, **regional**

### Assessing Biochar Quality

Currently, in the U.S., biochar quality is ascertained following the International Biochar Initiative (IBI) protocol [9]. Typically, producers conduct the laboratory testing and report the results but do not pay to certify their product with the IBI (only three biochar producers are listed as being certified on the IBI website as of 20 July 2020). A less-restrictive “organic-origin” protocol is also available through the Organic Materials Review Institute [22], which certifies compliance with the USDA’s National Organic Program regulations. Five companies have certified 24 biochar-containing products in the U.S. through OMRI (as of 20 July 2020). In Europe, the European Biochar Certificate [6] is a voluntary standard for wood biochar developed by the Ithaka Institute and used by several countries to ensure product quality. Currently, 18 biochar manufacturers or resellers have obtained the EBC, which costs approximately \$2,500 for extensive government-accredited on-site sustainability and safety inspection, laboratory testing, and labeling [25]. The EBC can be issued for four classes of biochar depending on end-use: feed (animal feed), agro, agro-organic, and material (various industrial uses). A “C-sink” certification option was recently added to the EBC to address the need for ensuring sustainable, climate-friendly biochar production. In addition to these standards, the IBI has proposed a biochar classification and labeling scheme [4]. This classification scheme organizes detailed information about a biochar’s properties and ranks its suitability to provide different benefits. ■

**market development efforts** require conduct of near-term research and pilot-scale demonstrations of biochar technology to **demonstrate how biochar can generate direct value** when used to address problems as diverse as soil acidity, low water-holding capacity, fire hazard reduction, abandoned mine land reclamation, composting odors and efficiencies, and stormwater filtration, as well as the development of new high-value C-based materials. In the sections that follow, we present proposals for work in these areas.

### Develop Protocols and Specifications

Ensuring sustainable production, product consistency and appropriate use is essential to market development of climate-friendly biochar. Sustainable production requires appropriate biomass sourcing and production with minimal emissions of environmental concern. Product consistency depends on the development and widespread adoption of biochar characterization and classification protocols (see sidebar “*Assessing Biochar Quality*”), coupled with simplified product labeling for

retail sales of biochar-containing products. Appropriate use at the industrial scale is enabled by development and adoption of contract specifications based on best management practices. At the retail scale, publicizing the availability of guidance documents and promoting the use of best management practices can help users achieve a consistent outcome.

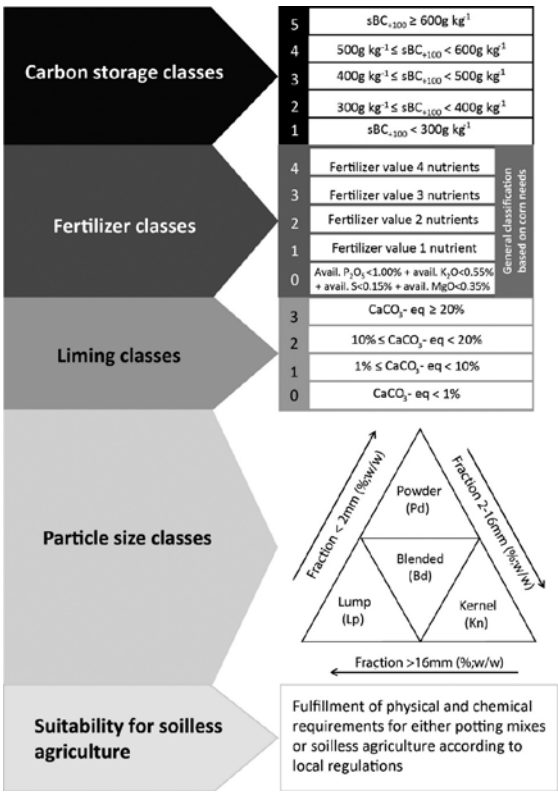
Despite having a larger market [36] and a smaller certification fee (\$500 vs. \$2,500, [25]), the adoption of the IBI biochar certificate in the U.S. lags that of the EBC in Europe. The European consumers of biochar products value the EBC highly enough that the price of biochar marketed without an EBC is roughly half of that with an EBC [25]. This fundamentally changes the market and explains, in part, the much higher adoption of biochar certification in Europe than in the U.S., even with the higher cost. Also, the higher population density and cost of energy in Europe support a mature district-heating and cogeneration infrastructure and make bioenergy more competitive with other sources of energy. European producers benefit financially by having a strong market for the energy co-generated during biochar production and thus are better positioned to absorb the costs associated with biochar certification. When the Organic Materials Review Institute (OMRI) organic-origin certification is considered, however, there is a rough parity in adoption rate between the U.S. and European systems. The U.S. lacks a “C-sink” type of certification that considers the sustainability and climate-footprint of the biochar production process. Perhaps because of this fragmented certification system in the U.S., frequent calls for developing/enhancing standards for biochar characterization and quality are heard in market surveys (e.g., [8]) even though many of those standards already exist.

To repair this fragmented certification approach, we recommend that funding be directed towards the development of a new unified certification standard, at least for the U.S. This standard would combine:

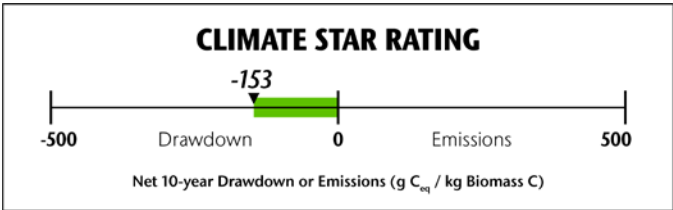
- a C-sink-type estimate (e.g., a “climate star” rating of production footprint in carbon dioxide equivalent [CO<sub>2</sub>e] per unit weight biochar, patterned after the “energy star” rating given to appliances by the U.S. EPA) with
- categories of certification based on end use of the biochar similar to those in the EBC, and
- a classification/labeling system (probably a combination of the climate star rating and the system proposed by Camps-Arbestain et al. [4]).

The classification system of Camps-Arbestain et al. [4] provides more detail than either the IBI or the EBC system. Biochars are classified on the basis of their

chemical and physical properties (such as particle size) and for their ability to provide different benefits including C storage, fertilizer value, liming, and as a medium for soil-less agriculture. These suitability ratings can be displayed concisely in a simple label (Figure 3.6) and could be combined with a climate star rating (Figure 3.7) that includes both production emissions and C-storage offsets per unit of biomass feedstock for a specified period.



**Figure 3.6.** A classification system of biochar based on its potential benefits. The C storage value ( $sBC_{+100}$ ) stands for stock  $BC_{+100}$  and is obtained by multiplying the organic C content of the biochar (Corg) by the estimated fraction of Corg in the biochar that remains stable in soil for more than 100 years ( $BC_{+100}$ ). Minimum levels for available  $P_2O_5$ ,  $K_2O$ , S and MgO are based on the needs to fulfill the demand of an average corn crop (grain) considering a biochar application of 10 tonnes per hectare. Units of available nutrients,  $CaCO_3$  equivalence ( $CaCO_3\text{-eq}$ ) and particle fractions are on % mass basis of biochar. Copyright 2015 From Biochar for Environmental Management: Science, Technology and Implementation by Lehmann & Joseph (Eds.) Reproduced by permission of Taylor and Francis Group, LLC, a division of Informa plc.



**Figure 3.7.** Example of a C-sink type of rating system that could be used to certify biochars for their net climate impact including C storage and production emissions (J.E. Amonette)

Provided that an “organic-origin” option could be added to each of the end-use categories (as appropriate), a single certification program could then cover all the important aspects of biochar production. Additional certification categories, such as for use in animal feed (currently not legal in the U.S. except for medicinal purposes), or even a combined U.S.-European standard with adjustments for specific national environmental regulations, could be added as new markets develop.

With respect to specifying and promoting appropriate use, we recommend that the best management practices developed (and periodically updated) in the long-term coordinated research and development program be prominently displayed on the website of the certifying organization (e.g., IBI) as well as form a strong part of the customer discovery process outlined under the Infrastructure to Support Business Development priority area, described below. We also recommend that funding be directed to help develop contractual language for appropriate use, and that this language could then form the basis for actions in our fourth major priority area, Collaborative Policy Development.

## Measure Environmental Emissions Factors

Because biochar production has the potential to alter air quality (from emissions associated with biomass conversion processes) as well as water quality (from releases of water used to quench the biochar), it is subject to local, state, and federal environmental regulations. In many instances, these regulations were developed for other processes, such as incineration and, in the absence of relevant emission data, regulators are restricted in their ability to treat biochar production as a distinct process. (See *Chapter 12: Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems*.)

To change this situation, we recommend funding a three-year near-term project that focuses on compilation and measurement of high-quality air (and where appropriate, water) emissions factor data for the suite of existing biochar-production methods. This would include portable flame-cap kilns used for small land-holdings, mobile units used at forest landings (gasifiers, auger-driven slow pyrolysis units, air curtain burners modified to enhance biochar production), large-scale gasifiers typical of biomass boilers, and both conventional and conservation pile burning methods used in forestry operations. Emission data would be collected for appropriate feedstocks (e.g., softwood, hardwood, straw, manure) when dry, and at relevant moisture

contents to simulate situations where pre-drying of biomass is not feasible. Emissions data would also be collected across a range of production temperatures (low, typical, and high) to give good coverage of potential operating conditions. Finally, to aid estimates of climate impacts, the C efficiency of each process would be determined by weighing the initial biomass and final biochar on an oven-dry basis and measuring their total C contents, and the emissions of GHGs (i.e., CH<sub>4</sub> and nitrous oxide) would be measured directly (in addition to the usual measurements of priority pollutants such as CO<sub>2</sub>, oxides of sulfur and nitrogen, volatile organic compounds (VOCs), and particulate matter smaller than 2.5 microns [PM<sub>2.5</sub>]).

In situations where water is used to quench the biochar, the amounts of water used and that are not volatilized during the quenching process would be measured, and samples taken of any runoff that might occur. Analysis of these samples for priority pollutants, together with biomass and biochar mass data, would be used to determine aqueous emissions factors per unit of biomass converted.

The results of these emissions factor measurements would be compiled along with those reported by others and used to construct/refine simple emission models for each biochar production method. These models would form the core of a scientifically defensible approach to recognize production methods with better performance, drive ongoing technology development, and assist in work with regulatory agencies to develop a regulatory framework that is more appropriate for biochar production.

## Develop Algorithms and Assess Market Values for Ecosystem Services

Finding ways to monetize the ecosystem services provided by biochar technology involves the development of algorithms, based on scientific understanding and data, that quantify the size and value of these benefits relative to various alternatives (e.g., wildfires, decay in place). Once the algorithms have been developed, mechanisms of funding to compensate producers and users can be established.

We recommend that near-term funding be directed towards the development of algorithms for quantification and valuation of four major classes of ecosystem service provided by biochar technology:

- Climate change mitigation,
- Soil health,



- Air quality and human health, and
- Water storage

We estimate that useful algorithms for each of these services could be developed, based on the existing science, over the course of a one-year project. The algorithms would be reviewed after three to five years and updated as scientific knowledge progresses. The work for each ecosystem service would be performed by a team having expertise in biochar production and use, economics, and the ecological/business/legal aspects of the service in question. Thus, for climate change mitigation, expertise in life cycle assessment and C marketing would be needed; for water storage, expertise in surface and groundwater hydrology, wildlife habitat, and water rights would be needed (in addition to biochar production/use and economics). Each team would review the relevant technical literature and adapt/develop a simple model that captures the ability of biochar technology to deliver an ecosystem service. For example, with climate change mitigation that ability would likely be measured in tons of avoided CO<sub>2</sub>e emissions, whereas for water storage, the units would be acre-feet of water storage. The team would then develop a way of valuing that service in a manner that enables the development of mechanisms to provide economic resources to pay the providers of that service.

Sponsorship of this work could come from state or federal government agencies, private foundations, or even private capital seeking to facilitate the monetization of these services. We also think this would be an excellent activity for funding by the proposed Endowment for Biochar-Based Community Development, which we describe later in this chapter.

## Conduct Pilot Studies and Demonstrations for Regional Market Development

The fourth major component in the near-term research and development priority area targets pilot studies and demonstrations of biochar in applications that have strong economic potential. In most instances, these technologies have been shown to work under a particular set of circumstances but need further development and demonstration to cement their utility for other applications or regions, thus clearing the way for market growth. We recommend funding of focused two- to three-year projects in the following categories:

1. **Prescriptive applications in agronomy, horticulture, forestry, and grassland management with potential to yield high near-term returns.** An example in agronomy could be development and

testing of a designer biochar to be applied to potato fields that would increase the efficiency of nitrogen fertilizer use thereby saving input costs and decreasing environmental impacts from leaching of nitrate and emissions of nitrous oxide. Another example, in the ornamental horticulture and forestry areas could be field testing of biochar/compost/soil mixtures to help establish young trees and minimize the use of unsustainable sphagnum peat moss. A third example, in grassland management, could be applications of biochar/compost mixtures on rangelands to strengthen biological diversity and increase water-holding capacity while simulating the eventual application of biochar in animal mineral supplements once Food and Drug Administration (FDA) approval is obtained. Work to test the impact of biochar in animal mineral supplements and provide data needed for FDA approval might also come under this type of project.

2. **Fire hazard reduction.** The need to thin small-diameter trees and brush in the wildland-urban interface areas of the arid and semi-arid west offers many economically promising opportunities for demonstrating the utility of biochar production as a way to offset some of the costs associated with the thinning while sequestering some of the C that would otherwise be lost to the atmosphere. When compared to the alternative of wildfire, portable gasifiers and slow-pyrolysis kilns (including flame-cap kilns) seem to offer immediate benefits. The feedstocks would come from local fire-hazard reduction operations or non-bid timber sales. As part of this effort, we propose assessing the level of progress made by fire-mitigation stewardship projects in the National Forest system. These “shelf-ready” projects would be identified through the NEPA Environmental Impact Statement process. An understanding of the outcomes of these projects would provide valuable insights into the most effective actions to take when proposing biochar-related fire-hazard reduction projects.
3. **Land reclamation and restoration.** Many abandoned mine-land sites are located in forested regions that either are actively harvested for timber or would benefit from thinning activities to suppress fire danger. Restoration of these sites using designer biochars to capture toxic metals, treat acidic soils, and increase water holding capacity to stimulate plant growth (see Project Example and Abandoned Mine Lands discussion in Chapter 5) is a prime example of the type of demonstration project we recommend funding. Another example is tied to removal of invasive

species such as conifers in oak forests of southern Oregon (Chapter 4) and Russian olive trees in the cottonwood riparian zones of the mountain states. In these instances, production of biochar could replace the dominant practice of pile burning thereby improving air quality, sequestering C in soils and stimulating growth of desirable species.

4. **Co-composting of municipal and agricultural waste.** Although much remains to be learned about the science of co-composting biochar with municipal organic wastes and with byproducts of agricultural processing facilities and animal containment operations, enough information exists to suggest that some demonstration projects can be implemented now for the purpose of eliminating odors and accelerating the composting process. These near-term projects can provide complementary information to that gained by the focused long-term coordinated research effort on this topic described earlier in this chapter.
5. **Environmental filtration.** In many instances, biochar can provide a low-cost substitute for conventional activated charcoal products. Two pioneering demonstration projects have already been conducted or are underway exploring removal of zinc from the rainwater shed by galvanized roofing to prevent its introduction to sensitive aquatic habitats [23] and removal of dissolved phosphate and nitrate from ponds to prevent algae overgrowth [18, 20]. More projects of this nature are needed to address specific regional issues and demonstrate the value added by biochar technology. One example, based on the well-known ability of biochar to sorb herbicides and pesticides [5, 10, 28, 30, 31, 32], would explore the use of filter strips containing biochar at the edges of agricultural fields as a way of minimizing runoff into surface waterways.
6. **Production of high-value C-based materials.** In contrast to the use of biochar as a high-volume, low-cost substitute for activated-charcoal filtration, we also recommend funding of projects that design and demonstrate the production of low-volume, high-value C-based products used as catalysts, battery electrodes, and reductants in specialty metallurgical operations. (See Chapter 6: Centralized Biochar Production Facilities). These projects would likely require special attention to feedstock purity, moisture content, and particle size, as well as to the design and operation of reactors that provide precise, reproducible pyrolysis conditions. Post-pyrolysis activation of these C-products by a variety of methods can further enhance their value.

As in the previous section, sponsorship of this work could come from state or federal government agencies, private foundations, and private capital seeking to develop new markets. These projects would also be ideal for funding by the proposed Endowment for Biochar-Based Community Development, which we describe in the next section.

## INFRASTRUCTURE TO SUPPORT BUSINESS DEVELOPMENT



The third major priority area we recommend for funding involves the creation and strengthening of the infrastructure needed to support the development of community-based biochar businesses. We organize our proposed efforts into three parts that focus on business formation, training a diverse workforce, and developing customer awareness.

1. **Foster business formation.** A number of actions can facilitate the formation of new biochar-based businesses. First, **providing a forum where entrepreneurs can make connections** with researchers, practitioners, and other businesses can lead to new partnerships and business ideas. This forum can also promote public-private partnerships, such as those where government agencies with intellectual property or specific policy mandates might co-fund projects with small businesses to develop new markets. Second, **providing guidance with respect to technical and regulatory issues** can help new businesses avoid expensive situations that lead to environmental contamination or economic failure. Third, the **development and sharing of business tools** such as planning templates and cost estimators specific to biochar production and application projects can help new businesses get established. Finally, **providing new and existing businesses with financial support** through direct access to capital, as well as creative financial instruments such as financing of purchase-orders and long-term sales agreements can make a big difference in the ultimate success of particular businesses, and of the industry as a whole.
2. **Train a diverse workforce.** The biochar industry has the potential to employ people with a wide range of skills and is well-suited to the economic development needs of rural and other underserved communities. Nevertheless, because biochar

technology is relatively new, some training is required and will help create a better environment for new businesses. This training can take the form of **student and summer internships, on-the-job training, and formal education from high school through to college undergraduate and post-graduate levels**. Funding to develop curricula and to support interns, employees, and students at all levels is needed to ensure that a well-prepared and diverse workforce is available to assist in the growth of the biochar industry (Figure 3.8).

3. **Develop customer awareness.** Any successful business endeavor builds on an intimate understanding of the needs of potential customers, develops a product that meets those needs, and builds demand for the product through a targeted marketing campaign that grows the customer base. We recommend continued funding to **survey stakeholders regarding current barriers to more widespread biochar production and use**. Examples of this sort of survey include recent reports funded by the USDA Forest Service Wood Innovation Grants Program [7,8]. Information gathered from these surveys can be used to align priorities for long-term research projects as well as near-term research and development projects and public policy campaigns. Once the product needed by the customer has been identified and developed, we recommend that the **design and conduct of marketing campaigns** targeted at both wholesale (e.g., nurseries and garden centers) and retail customers (biochar product end-users) be funded.

Implementation of these infrastructure-building actions follows two complementary pathways. First, we recommend direct funding to **support and strengthen the two primary trade organizations** that promote the biochar industry (IBI and USBI). However, we think that a new type of organization is also needed to focus on the financial aspects of the development effort. We propose creation of an **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 discussed previously. With respect to direct financial assistance to businesses the EBBCD would maintain a revolving fund to loan capital and finance purchase orders and short-term operating loans. However, a substantial portion of the EBBCD's mandate would be to catalyze funding for the near-term research and development projects needed to advance the biochar industry as a whole. The EBBCD would serve as a conduit for philanthropic funding and use this funding to identify and partner with stakeholders who need matching funds for federal and state grant programs as well as to provide seed money for promising new concepts. The primary emphasis of the EBBCD's program (and part of its appeal to large philanthropic donors) would be the development of small biochar-based businesses in rural communities.



**Figure 3.8.** A California Conservation Corps crew makes biochar in the Usal Redwood Forest. A McCleod tool is used to level the biochar in the kiln (left) so workers can measure the height of the pile. The CCC crew reacts to the information about how much carbon they sequestered that day (right). (Photos: Wilson Biochar Associates)



## COLLABORATIVE POLICY DEVELOPMENT

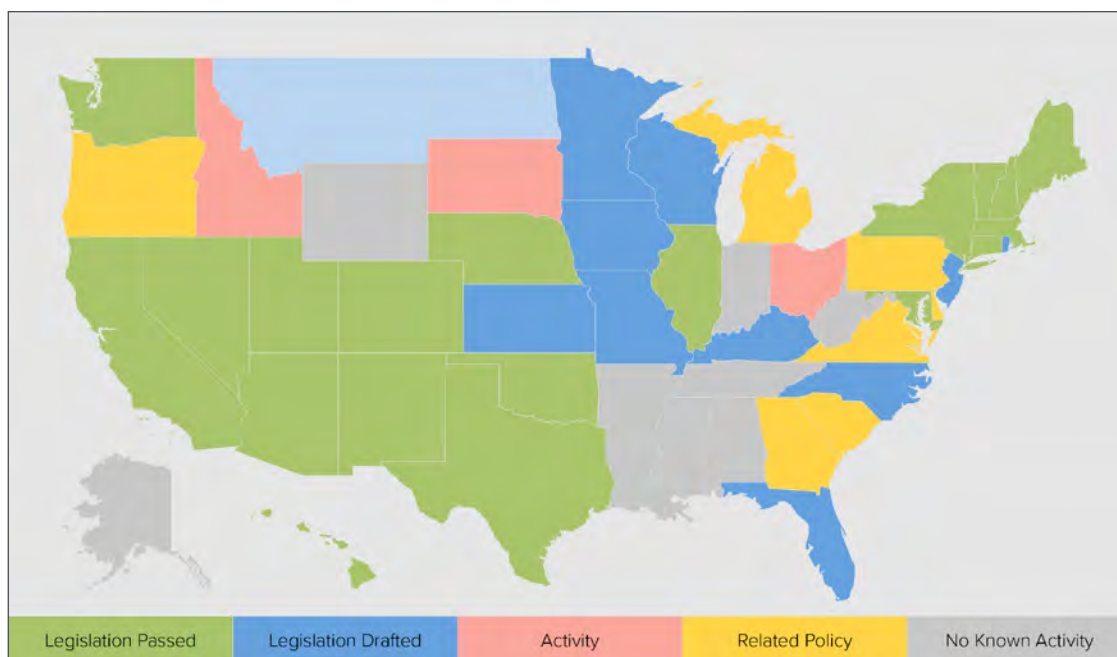


The fourth major priority area is the collaborative development of policies that support the goals of mitigating climate change, addressing wildfire risk, improving soil health, and revitalizing rural communities through the growth of a sustainable biochar industry. Collaboration with a broad range of stakeholders is an essential part of this process and will help ensure that the policies will be both effective and durable. We recommend that funding be prioritized to develop policies that enable price support for ecosystem services (with a near-term target on monetizing climate benefits) and that create appropriate environmental permitting instruments. Progress on policy issues will rely heavily on the development of scientific knowledge and its consolidation into Best Management Practices for regulated activities such as stormwater management, compost emission control, and nutrient management as part of the long-term and short-term research proposed previously.

### Price Support for Ecosystem Services

Policies that enable biochar producers, practitioners, and consumers to receive monetary benefit for the ecosystem services their actions support fall into two categories—direct price support through subsidies and tax credits and indirect support through policies that tax or otherwise raise the cost of undesirable alternative economic decisions. In the following, we give examples of each type of policy for the four ecosystem services provided by biochar technology.

1. **Climate change mitigation.** Direct price support would come in the form of C-storage and greenhouse-gas offset credits to biochar producers, landowners who incorporate biochar into their soil, and companies that substitute biochar C for fossil-based C in the products they manufacture. These credits are enabled by two market types: voluntary markets such as Climate Action Reserve, Puro.earth, or Carbon Future, and obligated markets such as the government-supported Cap and Trade mechanisms that collect funds from fossil fuel producers and redirect them in support of biochar technology. A current example of an obligated market is the California low-C fuel standard [13]. Indirect price support would come in the form of a tax or fee levied on the CO<sub>2</sub>e content of fossil-fuel
2. **Soil health.** The level of non-pyrogenic soil C, which can be increased by biochar amendments, is one of the primary indicators of soil health. Direct price support for adoption of practices like this that improve soil health would be similar in many ways to C-storage credits. A few such soil health programs already exist, including the NRCS EQIP program, which has an interim conservation practice standard for soil carbon amendment that will allow funding to be used for biochar application (code 808). States also have a variety of soil-health policies either active or in development to which biochar could be integrated (Figure 3.9). As one example, California's Healthy Soils Program, which utilizes funds from the California Cap and Trade program to support a variety of soil health practices on agricultural lands, does not currently have a management practice for biochar, but could incorporate this in the future. Governments and other organizations (such as the Soil Health Institute) interested in promoting these practices could raise funds to subsidize changes in farming and ranching practices that improve soil health. Indirect price support could come from the adoption of voluntary standards similar to those in place for organic food production that, in combination with public education, would allow producers who are certified as implementing soil health practices to charge more for their products.
3. **Air quality and human health.** Poor air quality stemming from wildfires and biomass open-burning practices harms human health, disproportionately impacts vulnerable populations, and burdens the healthcare system. Policies that provide direct price support to biochar producers and practitioners could be tied to publicly funded fuel reduction contracts in which the adoption of biochar production technologies would receive additional credits for the improved air quality resulting from less frequent wildfire. (See sidebar "Valuing the Unvalued") It should be noted that clean combustion of biomass with minimal production of biochar (using air curtain burners, for example) also would improve air quality compared to burning and thus both of these approaches would provide benefit compared to open



**Figure 3.9.** Status of state-level soil health supporting legislation in the United States, as of July 2021. (US State Soil Health Policy Map provided by Steven Keleti, Healthy Soils Advocate, on <https://nerdsforearth.com/state-healthy-soils-policy/>. This crowd-sourced policy tracker is hosted by Nerds for Earth, a volunteer group that provides technical support for rebalancing the earth's climate.)

### Valuing the Unvalued

There's potential to change the way that some publicly funded contracts are written to encourage recovery of biomass for biochar production, or even to provide additional credits for those employing biochar technology. For example, currently the U.S. Forest Service (USFS) writes some timber sales contracts to require the purchaser to consume "unmerchantable slash." If the USFS were to restructure sales to allow unmerchantable slash, the sale purchaser might work with those who have firewood, posts/poles, or biochar production needs; more of the wood already handled will avoid the burn pile and open burning of biomass concentrations. Meanwhile, USFS fuel reduction contracts often involve several treatment steps including mulching, "lop and scatter," and controlled underburn. In some cases, however, it may be possible to make a merchantable product, such as biochar, from some of the materials resulting from fuel reduction activities, which could be specified in the contracts with a policy change.

The USFS represents one major example of a public land management agency that could implement future policy changes to encourage the production of biochar. However, if other public agencies managing forests (e.g., federal, state, tribal) were to enact similar policies, the collective impact would be significant. Because both supply and demand are required for a robust industry, policies encouraging application of biochar, particularly in promising agricultural contexts are also important for growing the emerging industry and reaping the benefits of biochar. ■

burning practices. Other factors associated with biochar production (e.g., climate, soil health, water holding capacity) could help tip the balance towards implementation of biochar in many situations. Indirect pricing support would largely come from the implementation of regulatory or economic (e.g., taxation) policies that discourage open burning of brush piles and that mandate wildfire hazard-reduction practices. For example, a civil penalty or tax on private land where a wildfire hazard exists would indirectly stimulate efforts to remove the risk, especially if some public funds were also available to help landowners deal with the problem.

4. **Water storage.** Aside from the direct economic benefits that water storage brings by enhancing plant productivity on lands where biochar is applied, the enhancement of water storage capacity by biochar (see sidebar "Soil Water Storage with Biochar") can help minimize the size of flooding events. As a consequence, in specific areas where flooding is an issue, a policy by which national, state, and local flood-control districts would directly pay particular upstream landowners to apply biochar to their soils could make sense. After implementation, flood control payments could continue provided that the available evidence supported the maintenance of the improved water holding capacity.

## Appropriate Environmental Permitting Instruments

To be successful, biochar businesses need to obtain a range of permits, of which air quality permits can be particularly challenging. To address this issue, a range of strategies may be needed to smooth the regulatory pathway, and in some cases, to successfully develop new regulatory instruments that protect the environment without penalizing pyrolysis-based conversion of biomass to biochar. This will require a collaborative approach that is based on the appropriate use of biochar technology and the collection of high-quality scientific data to support development of the new policy instruments. We have recommended funding to develop and consolidate the scientific understanding needed to create these new regulatory instruments associated with environmental protection of air and water quality. Here, we simply 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.

## Implementation

We envision a four-stage collaborative process to implement recommended policy changes, led by the biochar industry trade organizations. Funding to support this process would come in part from the industry itself, but also from non-governmental entities (e.g., foundations, private venture capital) interested in seeing biochar technology implemented to help meet their goals related to climate change mitigation and rural community development.

The first stage of implementation is to 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. These stakeholders should include landowners, land managers (private, state, federal), environmental regulatory agencies, C-marketing organizations, private foundations focused on climate action and community development, tribes and indigenous practitioners, economic development organizations, and climate-oriented private capital. The results of this conversation may impact decisions made to develop and prioritize specific near-term research and development projects as well as policy recommendations.

The second stage, which overlaps in part with the first stage, involves the sharing of relevant research results with this group of interested stakeholders.

### Soil Water Storage with Biochar

Biochar can hold as much as twice its own weight in water when saturated. Like water retention by native soil organic matter [19], much of the water retained by biochar is held in large pores that drain readily after a few days (i.e., field capacity). This short-term buffering effect can serve to blunt some of the impact of large rain events on the runoff that leads to flooding. When added to soil, the effect of biochar is strongest in sandier soils and weakest in soils that are high in clay [21, 24]. For example, working in the laboratory with Washington soils and a wood biochar prepared by gasification, Zhang et al. [35] showed a relative increase of more than 72% in the retention of water by a sandy soil at field capacity when the soil was amended with 2.4% biochar by weight; a silt-loam soil showed a 29% increase and a high clay soil only an 8% increase. In absolute terms, these increases were about 3.9%, 7.9%, and 3.5% by weight for the three soils, respectively. A back-of-the-envelope calculation for a 5-cm rain event onto the dry sandy soil without biochar shows that the top 15 cm of the soil could absorb about 1.4 cm of the rain, leaving 3.6 cm to run off. When amended by 2.4% dry biochar, about 2.4 cm are retained, and only 2.6 cm would run off (a 28% decrease). ■

In the third stage, stakeholder coalitions would be formed to address and promote specific policy changes. Working groups would develop support documentation for the policy changes and draft specific policy language.

The final stage would involve promotional activity to implement and enable the new policy. This activity would likely involve developing general public support through media channels, and direct lobbying (by the members of each partnership) of governmental agencies and local, state, and federal legislators to enact any legislation needed to enable policy. In comparison to the first three stages, the final stage may take the longest to complete given the slow speed at which political change often proceeds in the U.S. However, with enough public support, change can happen quite rapidly particularly if the political ground is well-prepared by the process we have just outlined.



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