Biomass *to* Biochar

Maximizing the Carbon Value

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TABLE OF CONTENTS

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LIST OF ABBREVIATIONS

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

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

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

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Executive Summary

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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 (CO_2e T^{-1}) of dry feedstock. The amount of sustainably procured feedstock (typically waste biomass from forestry and agriculture) and the efficiency with which the C in it is converted to biochar, will ultimately determine the climate offset potential that is realized. A current estimate[1],

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

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

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

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

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

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

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

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

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

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

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

WORKSHOP OBJECTIVES

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

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

KEY CHALLENGES AND OPPORTUNITIES

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

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

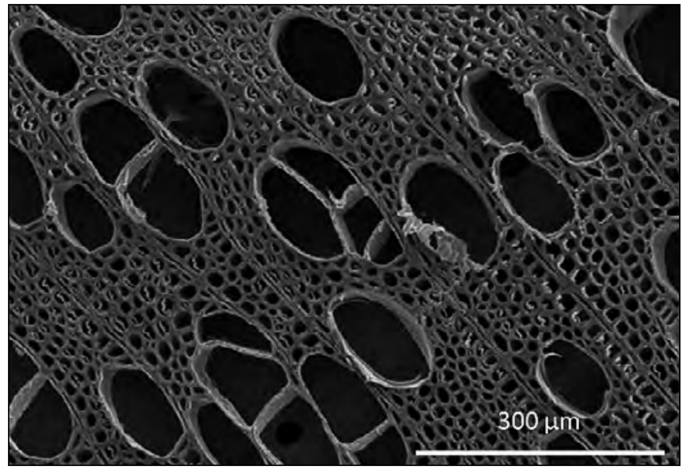

Figure ES-4. *Micropores in biochar vary based on feedstock type and pyrolysis temperature. Shown are electron microscopy images of biochar made from hybrid poplar. Reprinted from Biomass and Bioenergy, Vol 84, Suliman et al., Influence of feedstock source and pyrolysis temperature on biochar bulk and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

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

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

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

RECOMMENDED FUNDING STRATEGIES

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

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

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

Priority areas in *engineering* will be focused on lowering the cost of biochar by improving the efficiency of 1) biomass harvest and handling, 2) biochar production, handling, and post-production processing, 3) capture and utilization of bioenergy generated during biochar production, and 4) biochar application. To improve the climate impact of biochar production, work will be aimed

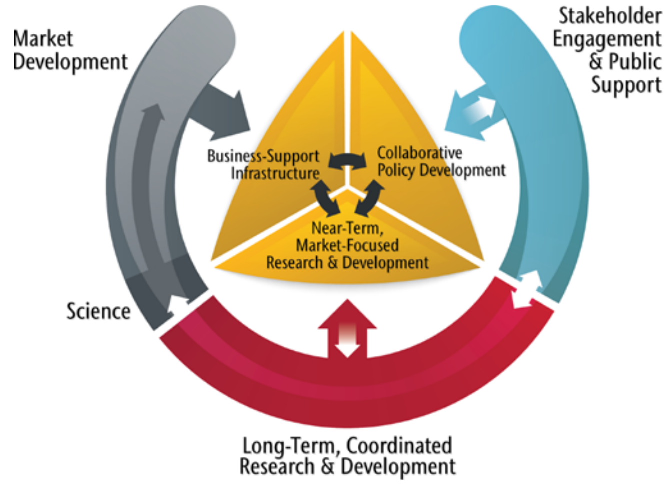

Figure ES-5. *Conceptual diagram of the relationships between the four major priority funding areas recommended by the workshop. Long-term coordinated research & development (in red) provides the foundational science and engineering needed to support development of biochar technology. Three closely related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

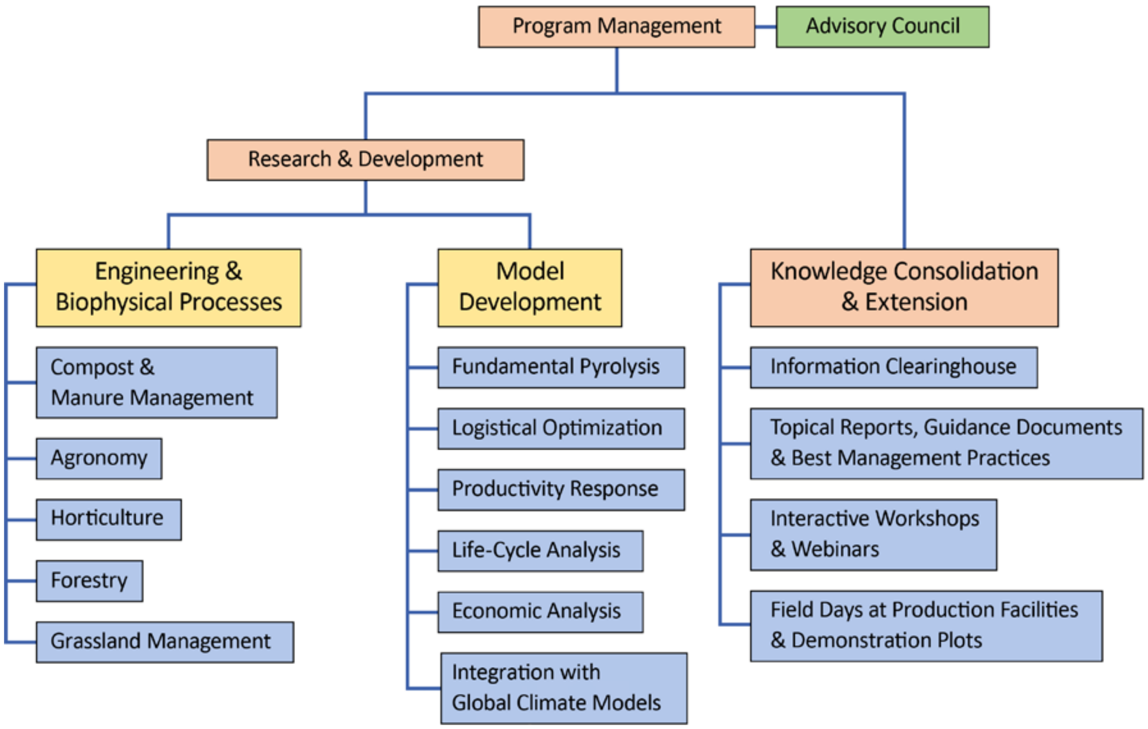

Figure ES-6. *Proposed long-term coordinated research and development program structure showing major groupings of activities.*

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_2e content of fossil fuel at the point where it enters the economy (wellhead, mine, port-of-entry).

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

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

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

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

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

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

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

SECTOR-FOCUSED FUNDING PRIORITIES

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

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

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

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

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

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

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

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

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

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

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

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

Table ES-1. *Biochar production processes.*

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

[1] Sectors are defined in Sector-Based Funding Priorities, above.
[2] Capacity: BDt = bone dry tons, 200 lb dry/cubic yard;
[3] C-conversion efficiency = 100*(tons biochar C/ton biomass C)
[4] Operations typically use up to eight units at a time.
[5] Portable air curtain incinerators/carbonizers, portable/modular retorts and gasifiers
[6] Combined heat & biochar, heated augers, fixed-location gasifiers.
[7] Wood boilers with capture/clean-up of re-injection ash
[8] This represents the portion (1.5% to 3%) of the total biomass feedstock consumed that is needed to maintain power output during biochar production. Total biomass conversion capacity ranges from 60 to 800 BDt/day and is mainly converted to bioenergy (heat and electricity).
[9] Uncertain due to variable fractions of biochar recovered and remaining in bottom ash under different operating conditions, but likely no higher than gasification.

CROSS-CUTTING TOPICS

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

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

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

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

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

MAXIMIZING THE CARBON VALUE

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

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

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

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

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_2e; 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_2), 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[1] (BD) tonne[2] (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 harvested 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[3] for C sequestration by biochar could

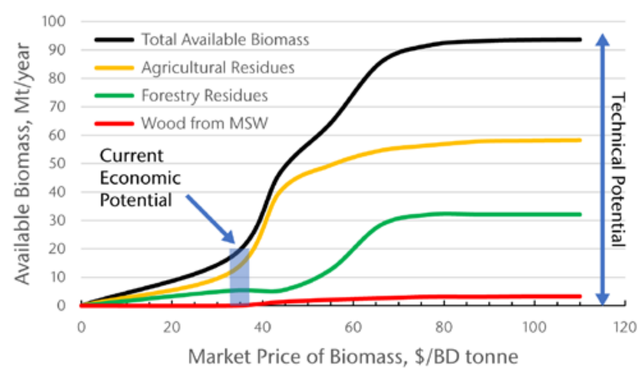

Figure 1.2. *Estimated available biomass for 2021-2030 from agricultural, forestry, and municipal sources in 17 Western States at different market prices [113]. Current biomass market price for forestry residues is about $35 per bone dry tonne [114]. Technical potential is reached at about $80 per bone 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_2e*

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)[4] 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[5]. 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_4) and soot, both of which have more powerful impacts on the climate than CO_2. The main goal, then, is to eliminate emissions of CH_4 and soot during production, leaving CO_2 as the only GHG emitted. Methods to complete the conversion of CH_4 and soot to CO_2 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.

4 *Which is equal to an increase of $13 per tonne [$12 per ton] C, or $3.50 per tonne [$3.17 per ton] CO_2e*

5 *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_2 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 quantify the net climate impact, however, a comparable set of emissions associated with the alternative fate of the biomass feedstock (e.g., natural decay, wildfire, land filling, etc.) also needs to be considered. At any point in time, subtraction of the cumulative alternative emissions from the cumulative biochar-technology emissions provides the net climate impact. When the emissions by biochar are lower than the alternative biomass pathway, the net emission are less than zero and the result is termed "C negative." In general, LCAs have indicated that biochar has a net climate impact of about -0.4 to -1.2 tonnes of CO_2 equivalents per tonne of bone dry feedstock (t CO_2e BD $tonne^{-1}$), meaning that the climate impact is beneficial (resulting in less CO_2 in the atmosphere). Increases in net emissions are possible with biochar, however, when purpose-grown feedstock is used and indirect land use change is included [25, 94, 95].

Because the impact of GHGs changes with time due to their different atmospheric residence times relative to CO_2, the climate impact will also change depending on the period being considered. A time-sensitive LCA approach fully captures this dynamic as shown in a hypothetical example for biochar and two alternative

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. ■

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_4.

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

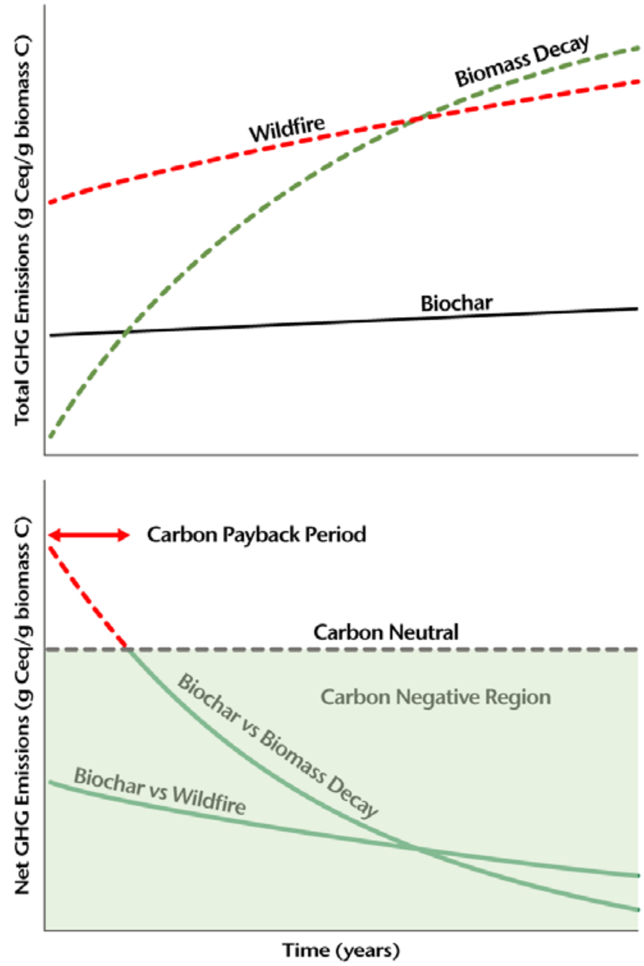

Figure 1.4. *Two stages in a hypothetical time-sensitive LCA of biochar technology. (Top) Total GHG emissions of biochar and two alternative fates of the same woody biomass feedstock (decay in place and wildfire). (Bottom) Net GHG emissions of the biochar approach relative to biomass decay and to wildfire. 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_2e per year. The highest, which was termed the "maximum sustainable technical potential," was 6.6 Gt (7.3 GT) of CO_2e 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 causes 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_2 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_2e offsets over 100 years. When on-site production at the forest landing was included, these values doubled. Applying the same approach here to

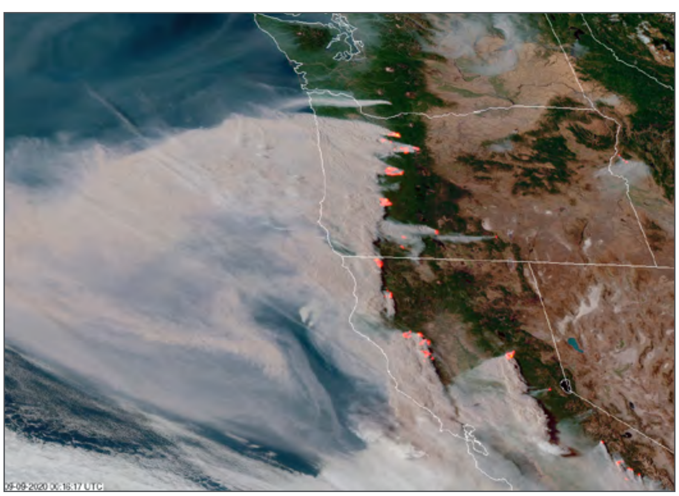

Figure 1.5. *Smoke and fires in the western U.S. visible from space on September 9, 2020. (Photo: rammb.cira.colostate.edu NOAA Satellites and Information)*

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_2e offsets[6] 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,

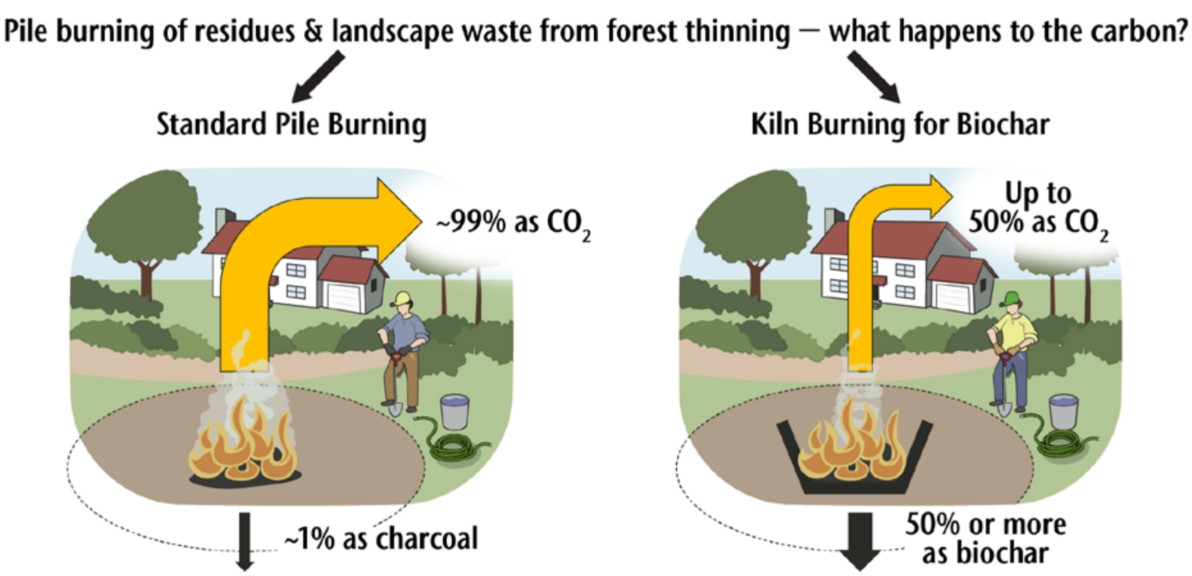

Figure 1.8. *Burning in a biochar kiln instead of a standard burn pile converts as much as half of the C in wood waste into biochar. Biochar lasts for hundreds to thousands of years in soil, benefiting forest health and sequestering C. (Figure adapted from CalFire)*

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

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

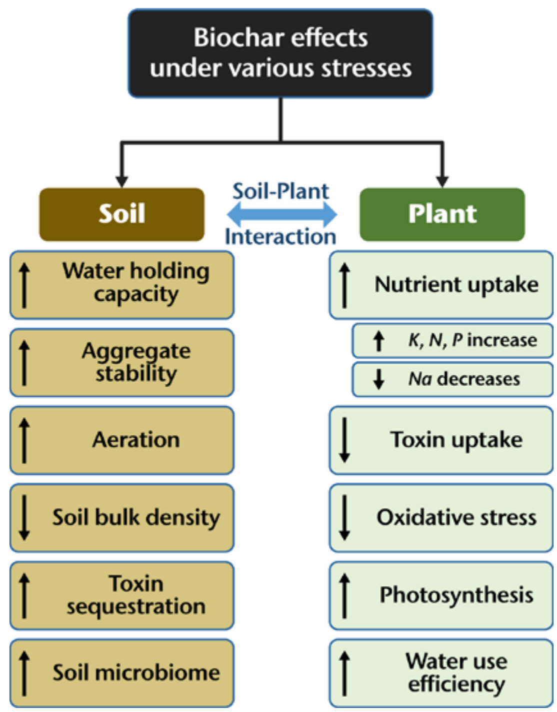

Figure 1.10. *Model of how biochar affects soil, plants, and soil-plant interactions under stressed conditions (Source: Gang 2018 [39])*

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_2 per hectare (1.4 tons CO_2 per acre) each year from the atmosphere (2.6 Gt [2.9 GT] CO_2 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].[7] 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.[8]

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-

7 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.

8 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_2 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_2e, 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_2e ($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_2e per tonne *biochar* at the time of soil application, and 1.8 to 2.3 tonnes CO_2e 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_2e could completely offset biochar production costs. Current market prices are in this range. Using a value of 2 tonnes CO_2e 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_2e per tonne biomass C [25,104,120]. Using this LCA-based approach with biomass data from Washington State[9], estimates of net C values range from a low of about 0.14 tonnes CO_2e per tonne biomass C at 5% C efficiency to a high of more than 1.5 tonnes CO_2e 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.

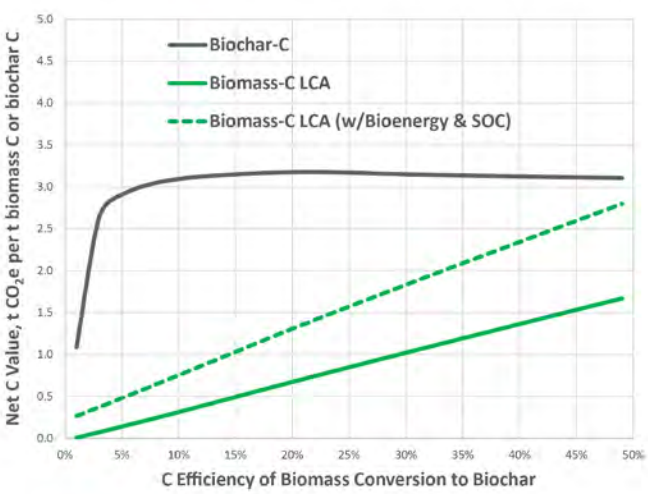

Figure 1.11. *Estimates of net C value for biochar systems in Washington State evaluated on the basis of biochar properties only (dark grey line) or with inclusion of C efficiency of biomass conversion (solid green line). The dashed green line adds the impacts of bioenergy generation and of biochar amendments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

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.[9] 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 (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[1] 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)*

1 *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,[2] syngas,[3] 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 thought 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_2, CO, and CO_2 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.[4]

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)*

4 *There are several initial efforts in this direction funded in recent years funded by the USFS Wood Innovation Grants program.*

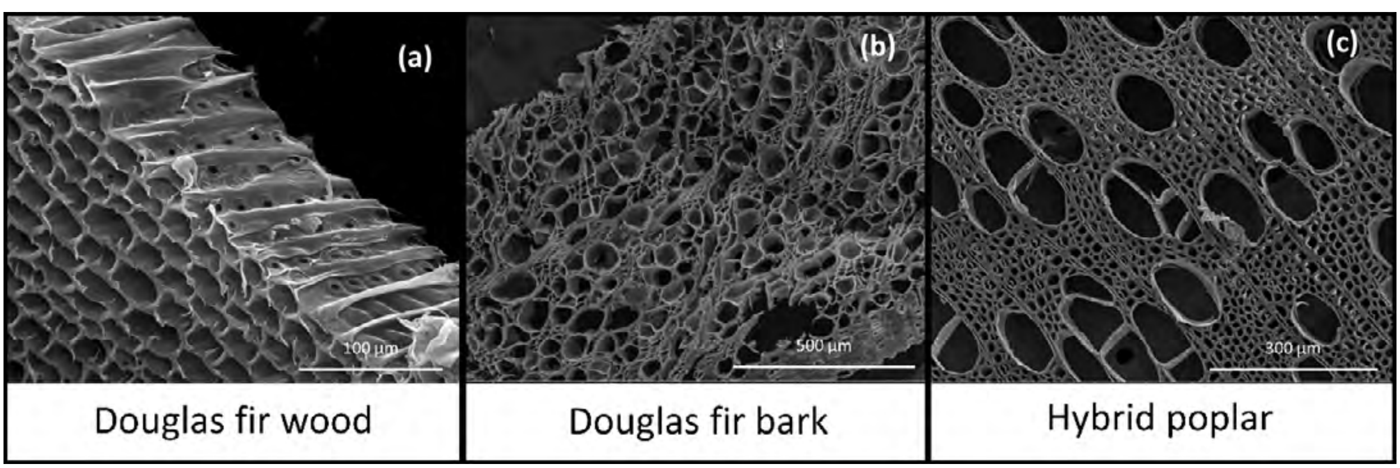

Figure 2.4. *Micropores in biochar vary based on feedstock type and pyrolysis temperature. Shown are electron microscopy images of biochar made from some typical feedstocks: Douglas fir wood, Douglas fir bark, and hybrid poplar. Reprinted from Biomass and Bioenergy, Vol 84, Suliman et al., Influence 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[5] of herbaceous feedstocks, and processed biochar products (such as mineral-enhanced or other functionalized products[6]). 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[7] (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

7 *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_2e]) 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_2e. 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_2e at the smaller scales (with one 500 tonnes [551 tons] biomass per year system yielding $365 per tonne [$331 per ton] CO_2e). 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.

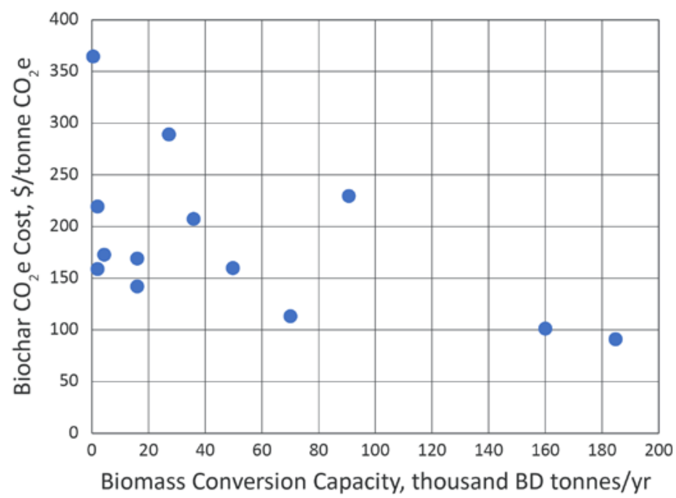

Figure 2.6. *Changes in the cost of biochar-generated offsets ($ per tonne CO_2e) with the scale of production (BD tonnes biomass converted per year). Economic data for biochar production selected from Shackley et al. ([38], Table 29.3) were combined with the following assumed data: Feedstock cost $70 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_2e 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[8] 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 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].

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

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

8 *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.[9] 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[10] and toxic air pollutants[11], 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_3), nitrogen oxides (NOx), carbon monoxide (CO), sulfur oxides, and lead (Pb). Volatile organic compounds (VOC), C-containing compounds involved in O_3 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[12]. 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 ($PM_{2.5}$) 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® 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 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.

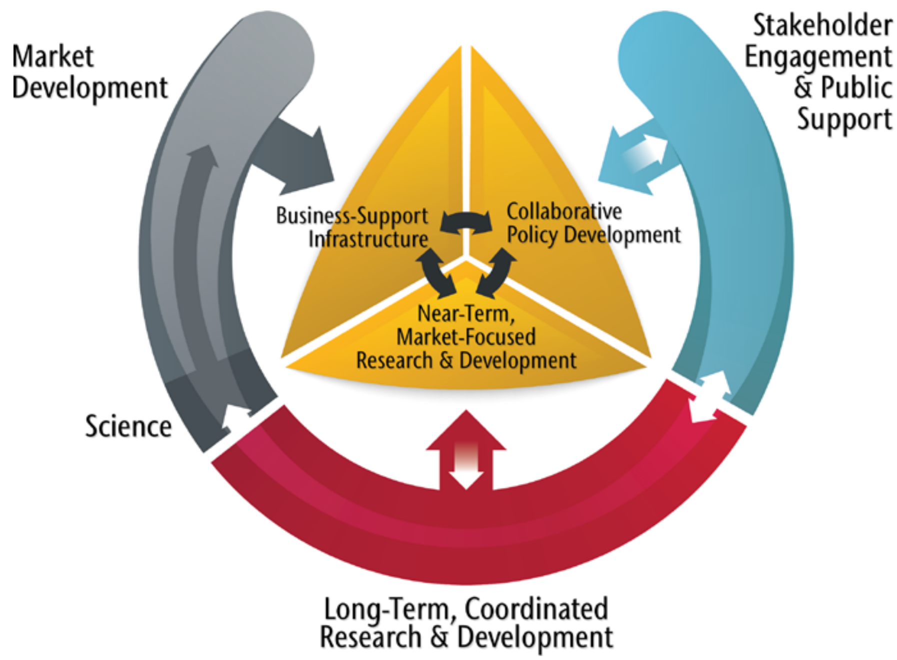

Figure 3.1. *Conceptual diagram of the relationships between the four major priority funding areas recommended by the workshop. Long-term coordinated research & development (in red) provides the foundational science and engineering needed to support development of biochar technology. Three closely related 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)*

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:

- P — Philanthropic organizations
- N — National governmental agencies
- S — State/Provincial governmental agencies
- L — Local governmental agencies
- C — Private capital

LONG-TERM MULTI-SITE COORDINATED RESEARCH PROGRAM

N S P C

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_4 and soot released to the atmosphere. The quality of the 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.

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

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.

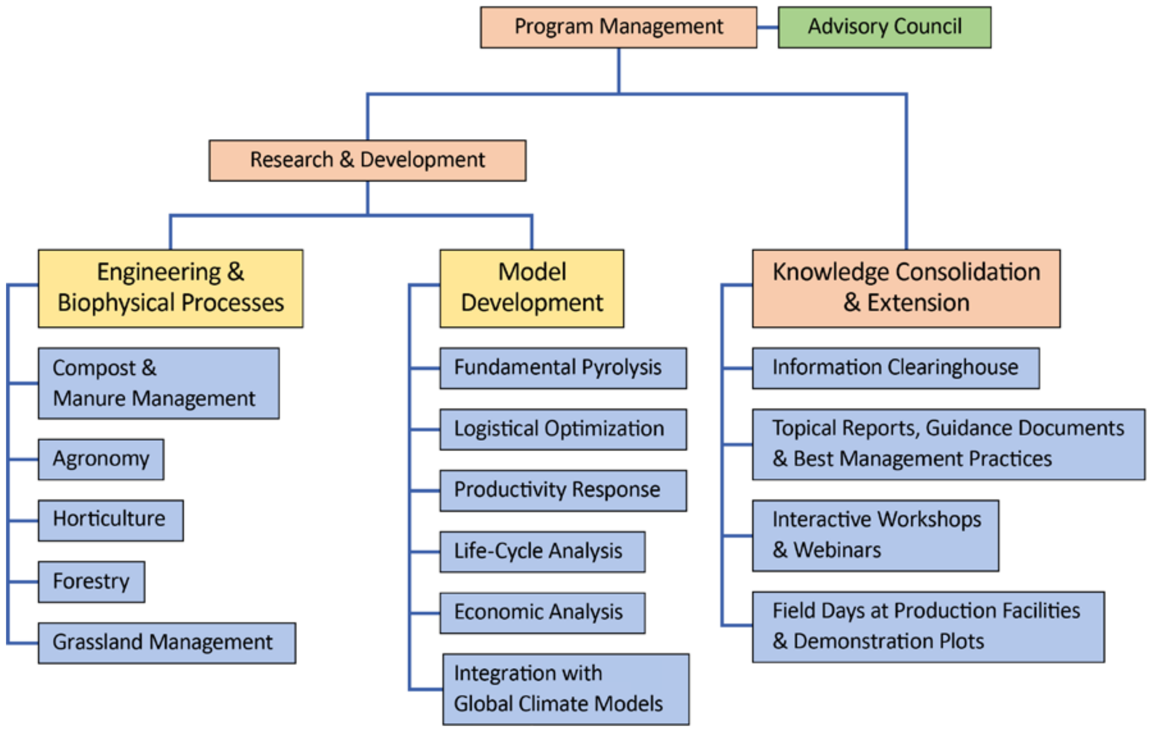

Figure 3.4. *Proposed long-term coordinated research and development program structure showing major groupings of activities.*

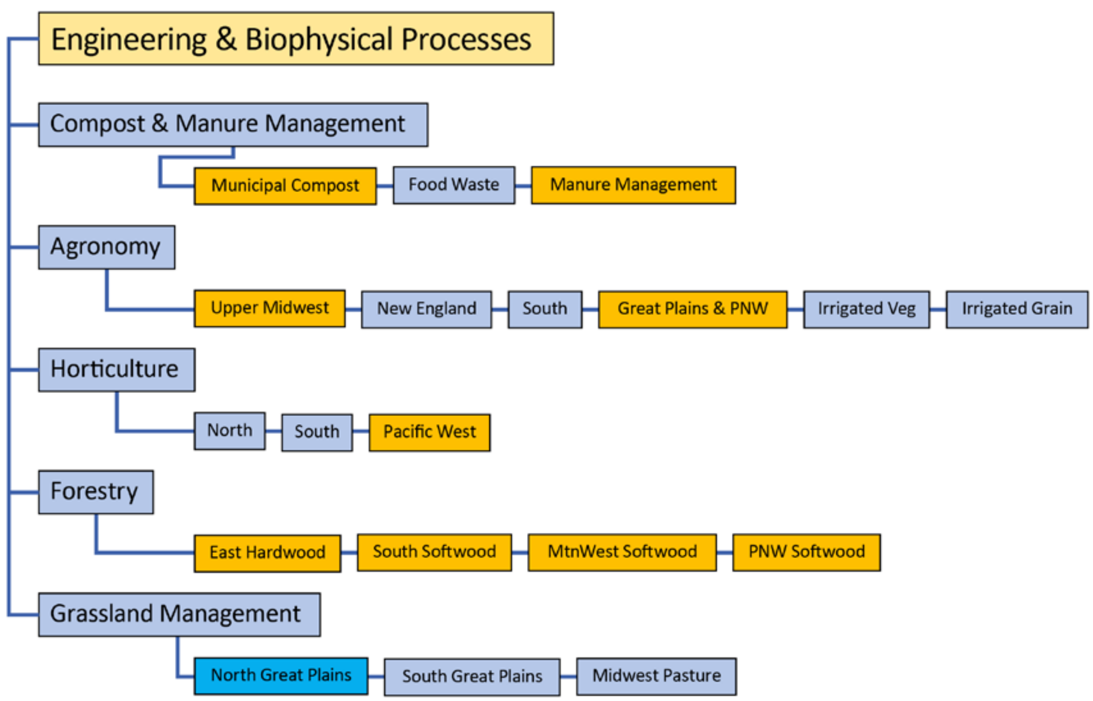

Figure 3.5. *Proposed topical/geographic sites for Engineering & Biophysical Processes efforts in long-term coordinated research and development program. All sites would conduct research on impacts of biochar amendments to soils. Orange-colored sites include biochar production and engineering capabilities;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

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. ■

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 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_2e] 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.

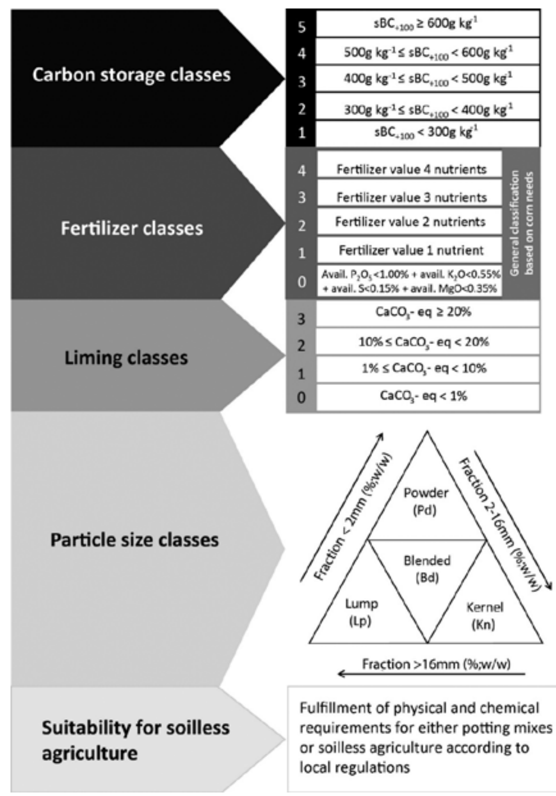

Figure 3.6. *A classification system of biochar based on its potential benefits. The C storage value (sBC+100) stands for stock BC+100 and is obtained by multiplying the organic C content of the biochar (Corg) by the estimated fraction of Corg in the biochar that remains stable in soil for more than 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 ($CaCO_3$-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.*

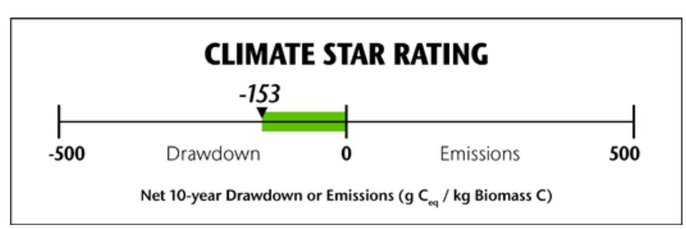

Figure 3.7. *Example of a C-sink type of rating system that could be used to certify biochars for their net climate impact including C storage and production emissions (J.E. Amonette)*

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 landholdings, 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_4 and nitrous oxide) would be measured directly (in addition to the usual measurements of priority pollutants such as CO_2, oxides of sulfur and nitrogen, volatile organic compounds (VOCs), and particulate matter smaller than 2.5 microns [$PM_{2.5}$]).

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_2e 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

P C N S L

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_2e content of fossil-fuel thus making bio-based and other low-C sources of energy more price competitive. Bio-based electricity production cannot compete economically with that produced by wind and solar, but it could compete in the production of heat energy. Indirect price support thus would benefit applications where the heat released by pyrolysis could be captured and utilized in applications such as warming of greenhouses, drying operations, or manufacturing processes.
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

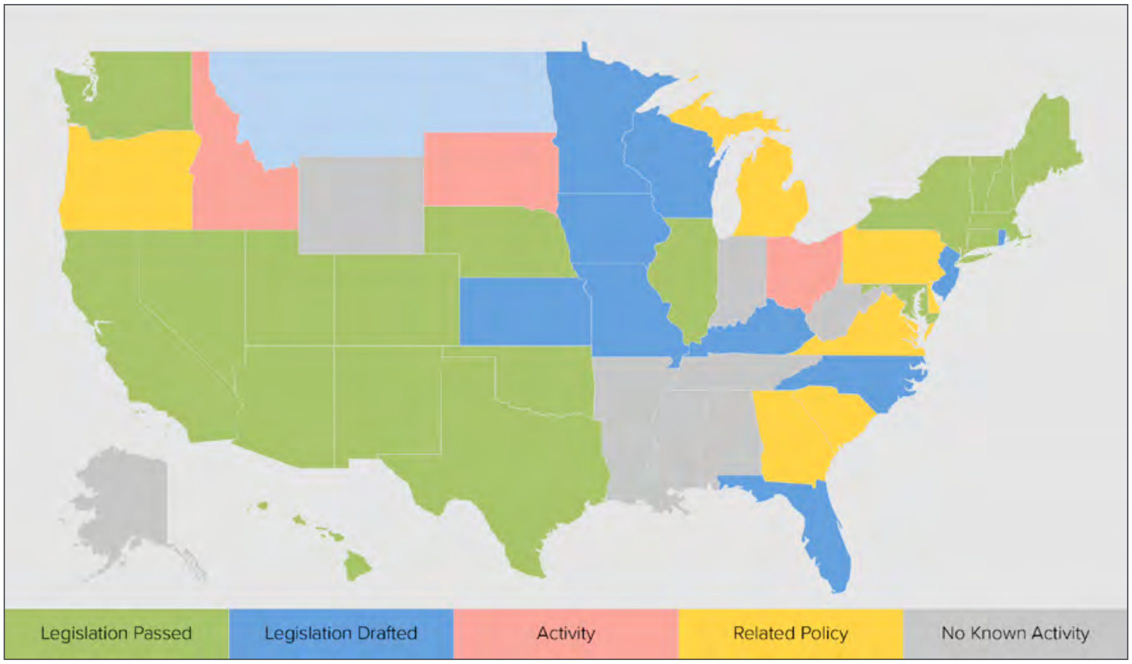

Figure 3.9. *Status of state-level soil health supporting legislation in the United States, as of July 2021. (US State Soil Health Policy Map provided by Steven Keleti, Healthy Soils Advocate, on https://nerdsforearth.com/state-healthy-soils-policy/. This crowd-sourced policy tracker is hosted by Nerds 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.

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). ■

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.

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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SECTION II:
Sector-Focused Analysis

This section contains a detailed analysis of five representative examples of biochar production and use in the PNW.

Chapter 4: Place-Based Biochar Production describes small (usually less than 500 tons per year woody biomass feedstock), labor-intensive manual operations with short distance transportation of biomass, with biochar used on-site.

Chapter 5: Moderate-Scale Biochar Production investigates temporary biochar production sites, often at forest landings, using skid-mounted trailer-sized conversion systems (usually 1,000-100,000 tons per year woody biomass feedstock) and involving some transport of biomass (less than 50 miles).

Chapter 6: Large-Scale, Centralized Biochar Production provides information on permanent biomass conversion facilities (usually greater than 100,000 tons per year woody biomass feedstocks) often with bioenergy production, and one-way hauling distances less than 100 miles.

Chapter 7: Biochar Integrated with Municipal Composting Facilities describes production of biochar from woody biomass collected from solid waste and its use as a catalytic agent in composting of organic wastes.

Chapter 8: Biochar Use in Agricultural Soils explores use of biochar produced at any scale as a soil amendment. Agricultural uses represent an important market due to the large volumes and potential climate mitigation and soil health benefits.

CHAPTER 4:

Place-Based Biochar Production

Ken Carloni, Gloria Flora, Kai Hoffman-Krull, Carson Sprenger, and Kelpie Wilson

INTRODUCTION

Place-based biochar involves the production and application of biochar onsite. Specifically, 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. The concept is inspired by Native American management practices that shaped the forested landscapes of the American West before the arrival of European settlers. One hallmark of these practices was frequent landscape burning that cleared the forest understory, leaving biochar as a byproduct. This created outstanding wildlife habitat and a forest ecosystem that was more resistant to extreme wildfire. The goal of place-based biochar practices is to clear the accumulation of excess fuels, while converting this biomass "waste" to a valuable resource—biochar. This will ultimately allow a safe return to broader and more frequent use of prescribed fire, improving habitat and increasing the resilience of our landscapes in a changing climate.

The methodologies defined in this chapter focus on decreasing the barriers for sustainable place-based biochar production utilizing technologies with low capital and operating costs but relatively higher labor costs. Given the pandemic and ongoing economic disruptions, local and state governments are now confronted with a need for economic recovery at a time where joblessness exceeds the numbers seen during the Great Depression. Just as the Civilian Conservation Corps helped save a generation from poverty, we propose that a modern model of a carbon focused conservation corps could help our current generation recover from both economic and climate catastrophe. Place-based biochar requires a large workforce for implementation, thus the money invested goes into the pockets of citizens productively employed rather than market capitalization for biochar production and transportation. This approach offers opportunities at a range of skill levels, from machine operators and arborists to students and disadvantaged workers.

The place-based sector of the biochar industry focuses mainly on the biomass left from a range of landscape maintenance and restoration activities. Foresters, orchardists, arborists, and other professionals perform these activities to maintain urban, forest and agricultural landscapes, restore habitat, improve wildfire resistance, and provide a multitude of other benefits. Biochar produced by these practitioners is used on or near the location where it is produced, furthering the restoration and resilience objectives of the vegetation management projects by reducing hazardous fuels, sequestering carbon, and improving soil health.

The volume of urban wood waste from construction, demolition, and yard maintenance exceeds the volume of timber harvested in forest management on an annual basis (McKeever & Skog 2003). However, in urban settings, this material is often generated where open burning is not feasible. Woody material is typically loaded into dumpsters and hauled away, usually with disposal fees involved. The potential fates of the carbon in that biomass generally do not lead to long-term storage.

In forestry applications, post-treatment slash is often unevenly distributed and difficult to access. The slash left after these operations far exceeds the amount necessary for nutrient cycling, protection of seedlings and mulching soil. This excess material becomes highly flammable as it dries out, significantly increasing the mortality risk of the remaining trees, as well as impeding wildlife travel and successful natural regeneration. The current practice is to simply create slash piles by machine, or by hand on rugged ground, cover them with plastic or waxed paper until dry, then light them and burn them as completely as possible.

Because of these limitations, this biomass is viewed as a problematic waste, requiring investments in time, dollars, and energy to manage and dispose. This net-loss management frequently leads to premature release of carbon into the atmosphere, negative air quality impacts, and missed opportunities for long-term carbon storage and economic and environmental value-added benefits.

WHO ARE WE?

Place-based biochar producers fill a broad niche in the biochar production ecosystem. The writers of this chapter include biochar contractors, educators, and engineers who use transportable flame-cap kilns (typically less than 10 cu. yd. capacity) to char non-merchantable woody biomass on site. We represent a small but very broad sector of the biochar industry including:

Small woodland landowners: Family and individual forest landowners make up more than 60% of all private forest ownership in the United States according to the U.S. Department of Agriculture (USDA 2015). Biochar production can be integrated into a range of forest management objectives ranging from commercial logging to restoration or fuel treatments. Increasingly, the knowledge of ecological benefits of biochar production, integrated with economic and engineering best practices, offers an opportunity for excess biomass to be returned to the forest floor either directly by the landowner or through a hired contractor. The Natural Resource Conservation Service (NRCS) now offers a cost share program to landowners for on-site biochar production through their *Conservation Stewardship Program.*

Land management organizations and agencies: Nonprofit and governmental landowning organizations and agencies often have ecologically based missions and can incorporate biochar into their management plans if they have a clear understanding of costs and benefits. Biochar can be used for soil improvement, carbon sequestration, and remediation, for example, in abandoned mine reclamation.

Low tech (but innovative) "backyard" producers: The techniques used in place-based biochar production were mostly developed by independent "backyard" experimenters.

Permaculturists, community educators: As an extension of missions of regenerative design, restoration and education, permaculturists and community educators practice and demonstrate sustainable biochar production and use techniques. Community educators may be part of a formal organization, such as Extension Service associated with state universities, or informal groups. For example, the Umpqua Biochar Education Team is an organized group of experimenters based in Oregon that received a Conservation Innovation Grant from the NRCS specifically to develop these techniques. Any of the other practitioners listed can serve as community educators.

Small farms, vineyards, orchards, forest-to-farm: Increasingly, small farmers are learning about and adopting low tech biochar production methods, especially where they have woodlots to manage. Making biochar and using it on the farm is a way of managing woody biomass while making a valuable input for manure management, compost, and soil.

Urban foresters and arborists: Arborists are interested in adding biochar to their services as an alternative to chipping and hauling brush and tree limbs. Biochar can provide another revenue stream and it also offers a clean way to dispose of waste wood without generating the noise and diesel emissions of chippers or incurring tipping fees. City park managers are increasingly interested in making and using biochar in landscaping, tree planting and turf grass installation.

Habitat restoration contractors: A number of public agencies (e.g., NRCS, U.S. Fish and Wildlife Service, state departments of natural resources) are beginning to pay landowners to convert their woody residue to biochar, and a small but growing number of forestry contractors have begun to integrate biochar into the other services they offer their clients.

Wildland firefighters: Firefighters who are performing vegetation management in the off-fire season have the needed skill set to manage the techniques for place-based conversion of forest slash to biochar.

Uneven-age forest management professionals: Forest managers who strive for multi-cohort stand structures are often unable to use broadcast burning in the way that clearcut/plantation foresters can. Biochar production offers them a safe way to dispose of logging slash in the understory without endangering the overstory trees.

OPPORTUNITIES

Integration with Forestry

Place-based biochar offers the most direct method for the forestry sector to process their biomass and utilize it as an amendment to forest soils. As fuel treatments and forest restoration activities increase to address the rising risk of wildfires across the nation, landscape biochar technologies can be adopted across the forestry sector. Place-based technologies work well over many types of terrain, providing access through machinery that is transportable with low soil compaction. Biochar has shown extensive value as a forest soil amendment with demonstrated improvements in forest soil health after biochar application (Li et al. 2017) through:

- increasing soil carbon
- increased water and nutrient retention capacity
- increased soil porosity
- increased moisture retention
- higher soil pH
- enhanced biological activity

A meta-analysis by Thomas et al. (2015) found that soil health improvements as a result of biochar addition increase tree growth responses, with an average 41% increase in biomass with pronounced results in early growth stages. Place-based biochar production also provides a ready source of biochar for improving forest soils and for managing environmental challenges created by forestry activities such as compacted soils, erosion, and re-vegetation challenges. This increase in soil health comes at a time when climate change will increasingly place our forests under greater stress. Keeping our forests healthy and resilient will be one of our greatest tools for addressing climate change, as globally forests absorb 2.4 billion tons of carbon dioxide (CO_2) each year, about a third of the CO_2 released by burning fossil fuels (Pan et al. 2011).

Potential for Broad Adoption

We examined the barriers to the wider acceptance and practice of place-based biochar production. Compared to other biochar producers discussed in this report, we are at the smallest scale in terms of daily throughput of biomass per kiln or thermochemical conversion device. The often remote and patchy distribution of our feedstock means that opportunities for scaling up the size of our equipment or the mechanization of our operations are limited. Therefore, it makes more sense to scale out this sector by fine-tuning the technology and honing operational efficiencies to develop standards and best practices for our industry. These can then be replicated by a wide range of operators, either by incorporating biochar production in their current operations or by specializing in this process.

Given that we live in a time of mass unemployment, our approach has the potential to scale widely across the landscape to treat thousands of acres and produce significant quantities of biochar while providing meaningful employment to thousands of people who need jobs. While place-based biochar methods are typically small-scale batch technologies, the collective impact of these could be very large because of the diversity of applications. Beyond forest landowners and the forest industry, the low barriers to entry make onsite biochar production an accessible option for local farms, permaculturists, gardeners, ecology organizations, and schools who can all directly engage with this technology. The low technical and financial barriers for entry mean that it can serve as a market entrance point for a broad group of practitioners with little financial risk. Some methods of production require minimal financial investment, and simply require education to alter existing practice. Place-based methods represent a democratic form of biochar production, offering open-source designs and methodologies to people interested in amending their soils with biochar. Place-based biochar also offers potential for collaboration with the organizations that provide education and outreach to the end user, including forest collaboratives, soil and water conservation districts, forestry extension services, fire districts and air districts.

Coordinated Place-Based Biochar Research, Training, and Resources

We recognize that increasing the pace and scale of biochar integration with our audience requires compiling the appropriate information and data as well as making this information accessible. There is the potential to create a centralized online and training network for information and education on place-based biochar that offers guidance in production design, education, research, permitting, and policy. The scalability of place-based biochar will depend on developing a curriculum that is science-based and accessible to both trainers and end users.

This network could also serve as an organized repository for research on the impact of biochar. This repository could utilize an open and shared database where researchers can ask questions collectively and collaboratively across disciplines. Collaborative and open data provides the opportunity to build upon existing research and generate newer and more relevant questions. As the climate changes and new questions continue to emerge, shared and collaborative data offers collective insight into both the problems and solutions.

The centralized online location can also offer assistance accessing financial resources for landowners, such as information on carbon credits or cost-share funding. These areas of assistance include projections on financial return, access to funders and assistance with applications and reporting.

Place-based biochar offers an entry point for organizations, landowners, and governments to build confidence in biochar and increase their interest in larger-scale production and application systems. Place-based biochar production and on-site use could become the common practice for reducing excess biomass and disposal of woody slash and debris for forests and farmland. These practices would be reinforced by a network of research, training, and resources that invest in the resilience of our landscapes as we continue to adapt to a changing climate.

CHALLENGES TO IMPLEMENTATION OF LANDSCAPE-BASED BIOCHAR

Place-based biochar production intersects with many other environmental and resource concerns. To be successful, it requires a trained workforce and an educated public. It can also benefit from refinement of techniques, learning from other industries, expanded markets, and supportive public policy. To understand the challenges before us, we have divided them into four categories that we will treat separately below:

- Engineering
- Economic
- Ecological
- Engagement/Education

Engineering Challenges

Background

Over the past decade, many individuals worldwide have invented and developed small-scale flame-carbonizing devices. These have been deployed most widely with smallholders in developing countries who mostly pyrolyze crop waste, and with forest managers everywhere who use them as alternatives to burn pile incineration for waste disposal. These technologies are passive devices with no moving parts. Inventors have made many advances in design that improve efficiencies and reduce emissions of pollutants.

Flame-cap kilns are the primary pyrolysis technology currently used for place-based biochar. Flame-cap kilns are a type of gasifier that produces biochar in an open flame (Figure 4.1). In some cases, specially constructed and managed open burn piles are also used to make biochar. The use of unprocessed biomass residues is a key defining feature of landscape-based biochar production.

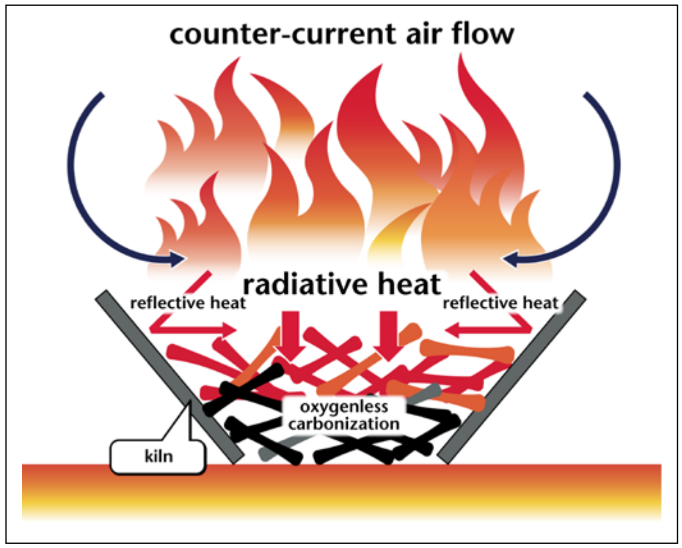

Figure 4.1. *Schematic showing basic operation of a flame-cap kiln. (Source: WilsonBiochar.com)*

A flame-cap kiln is a simple container that can be made from an earthen pit, bricks or ceramics, or metal. Only the metal kilns are portable. Kilns can have any shape, including cylinders, cones, troughs, pyramids, rectangles, or polygons. They should have an aspect ratio of height to width that is 1:1 or less. A kiln that is too tall will have trouble getting enough air to maintain combustion. The basic principle of operation is that of counterflow combustion. All combustion air comes from above. The air feeds a flame that is always maintained. The flame heats the feedstock below by radiation, which emits gasses that are burned in the flame. The flame consumes all the available air, so that no air is available to burn the char that forms beneath the flame. The counterflow combustion air keeps the flame low and prevents emission of embers or sparks. The flame also further combusts organic compounds in the smoke, reducing emissions of harmful compounds. Periodically, new feedstock is loaded into the kiln. This temporarily interrupts the flame-cap which is quickly reformed. When the kiln is full of char, it is quenched either with water or by snuffing with a lid.

With properly prepared and dry feedstocks, the biochar conversion efficiency of a flame cap kiln can rival that of industrial pyrolysis kilns. If well-managed, a flame cap kiln can convert biomass to biochar with an efficiency of up to 22% by weight (Cornelissen et al. 2016). It is important to recognize that this is accomplished with no other energy inputs for heating.

On very remote and steep sites, the best option may be to use newly developed open pile burning techniques for char production. This "Conservation Burn Pile" technique begins with constructing a clean pile that is loose enough to allow air flow and does not contain large amounts of dirt or rock. The pile must be lit on the top and allowed to burn down to the glowing coal stage. Then the fire is extinguished using water or a shovel before the char burns to ash. Top-lighting ensures that most of the smoke is burned, reducing emissions. Quenching before complete incineration preserves the char and protects forest soils from incineration and destruction of the organic soil horizon.

While there are further improvements to be made in flame carbonization methods and equipment, in forestry settings, the primary technical challenges are in feedstock handling and preparation. Widely distributed forest residues need to be gathered and transported to areas where kilns can be set up and where water is available for quenching. Some combination of hand work supplemented by machinery for moving feedstocks is appropriate for most landscapes. However, terrain, feedstock distribution, and access vary widely.

The biggest need at present is to develop protocols for different situations, along with costs, so that biochar jobs can be specified and implemented in a consistent fashion. Below we discuss the priority engineering challenges that should be addressed, categorized as kiln design, kiln emissions, feedstock preparation, feedstock comminution and handling, kiln loading, biochar quenching and handling, and landscape tiers for project design.

Scope of Engineering Challenges

Kiln Design

Kiln design should be based on two primary factors: feedstock and size. For instance, if feedstock is mostly forest slash less than 4 inches in diameter and less than 25% moisture, a kiln that is 5 to 6 feet across will generate enough heat to pyrolyze the feedstock. A larger kiln can also handle longer branches and boles, with less need for cutting to length. Kilns that are too large are more difficult to move, especially if used off-road. Larger kilns also generate more heat, which can be a concern for exposing workers to heat stress. Adding a heat shield surrounding the kiln body reduces heat loss, improves biochar conversion efficiency, and reduces emissions, but adds to the cost and complexity of kilns. More work is needed to optimize kiln designs for specific feedstocks and feedstock moisture levels. To date, this engineering development work has been done by individual entrepreneurs with little outside help. A small amount of investment in an organized program to compare and compile results could produce and disseminate more optimal designs.

Kiln Emissions

There is a great need for emissions measurements of different flame-cap kiln designs using different feedstocks, especially feedstocks with different moisture levels, including freshly harvested green material. The small amount of data we have indicates that flame-cap kilns are significantly cleaner than open burn piles. Visual assessment of emission opacity confirms that flame-cap kilns (Figure 4.2) emit very little particulates as compared to standard open burn piles. A robust set of emissions measurements for flame-cap kilns can help to assess kiln design modifications and lead to guidelines for feedstock specifications and loading rate practices. Information on U.S. Environmental Protection Agency criteria pollutants and hazardous air pollutants will help regulators understand how and when to permit flame-cap kilns. Greenhouse gas measurements will allow for accurate carbon accounting and life cycle assessment.

Figure 4.2. *Backyard biochar production using the Ring of Fire flame-cap kiln in April 2020 in Cave Junction, Oregon. Counterflow combustion keeps the flame length low and holds heat in the kiln for greater efficiency. Most of the smoke generated is burned in the kiln. (Photo: WilsonBiochar.com)*

Feedstock Preparation

Preparing forest slash materials for biochar production is similar to preparing those materials for burn pile incineration. The main difference is that branches and boles may need to be cut to a shorter length to fit inside a kiln. This would imply slightly more chainsaw cuts if for instance a 6-foot length requirement was changed to a 4-foot length requirement. Feedstock diameter limits are also key to biochar production efficiency in a flame-cap kiln and are shown in Table 4.1. Material that is greater than 6 inches in diameter is more difficult to convert to char, as the heat needs to penetrate to the center of the log in order to pyrolyze it. When working on the landscape, this thicker diameter material is best left on site where it has multiple ecological functions. From a vegetation management point of view, this larger diameter material is not a fire danger and does not need to be incinerated for disposal. However, where leaving more of the larger size material on the ground interferes with other management objectives, land managers may need to identify alternative treatments.

Table 4.1. *Three types of flame-cap kilns. (Source: Wilson Biochar)*

	Small Bin Kilns	Large Bin Kilns	Panel Bin Kilns
Mobility	ATC, Hand Crew	Road-based	Hand Crew
Feedstock diameter	Up to 4"	Up to 8"	Up to 4"
Feeding	Hand fed	Machine or hand fed	Hand fed
Quenching*	Flood	Flood	Spray and Rake
			
	Oregon Kiln	*Big Box Kiln*	*Ring of Fire Kiln™*

** All kilns can also be snuffed with a lid.*

Feedstock Drying, Collection, and Handling

Once the material is cut, it needs to be moved. In standard burn pile treatments, material is immediately stacked into carefully constructed "jackpot" piles and covered with polyethylene sheets to protect them from winter rains. In biochar treatment areas, material may be left in place to be gathered later and loaded into a kiln, or loosely windrowed and covered with polyethylene. In some cases, small diameter material can be cut green and immediately charred in a kiln with very little loss in conversion efficiency. If material is left in place uncovered, it should be processed in a kiln in late fall before winter rains have started in earnest.

There are many possible methods for feedstock collection, including whole-tree yarding[1] to a roadside. Off road vehicles can be useful for moving piles of feedstock closer to kilns, reducing the need for workers to walk. These options need to be explored and documented for different scenarios depending on road access and terrain. Most importantly, the costs of various options need to be evaluated, as described in the Economics section below, to support job planning and logistics.

Kiln Loading

Biochar kilns are loaded by hand. Workers require training to do this with the greatest efficiency and lowest emissions. If kilns are loaded too fast, the flame front moves upward and the radiant heat from the flame is not able to char all of the fuel. Unburned fuel will remain in the kiln. If the kiln is loaded too slowly, more of the material may burn to ash, reducing efficiency. Workers must be aware of feedstock species, size and moisture level and must be able to adjust loading rates and practices accordingly. Worker training and safety protocols are crucial to the success of landscape-based biochar. Given the number of workers needed, training programs will need to be well-organized and widely available.

Biochar Quenching and Handling

There are several options for recovering biochar and using it on site. Where water is available, biochar is easily quenched. One cubic yard of biochar can be quenched in a kiln with less than 50 gallons of water. For example, a 500-gallon fire truck parked on a road and utilizing a one inch line can be used to quench ten kilns up to a quarter mile away. Biochar can be quenched with little to no water just by spreading it thinly over the ground so that it loses heat (Figure 4.3). Five gallons of water in a backpack pump, combined with raking, can quench a cubic yard of biochar. Using a lid to snuff a kiln is also an option (Figure 4.4). We need further analysis of the time and costs for each of these options in the field.

Landscapes Tiers for Project Design

Current systems for fuels reduction and disposal on site are well-established with set costs per acre based partly on fuel density and partly on terrain and access. Contracting agencies may divide jobs into tiers based on these factors and provide differential pay rates for different tiers. Planning a fuels reduction project specifically for recovery of biochar from slash will change how fuels are cut, piled, and processed. Biochar kilns and quench-

1 *Yarding is the practice of, after felling, using a cable to pull an entire tree to a centralized location or roadside. There limbs and branches are removed and the tree bole cut to transportable lengths. This removes the need for brush piling and concentrates all slash in accessible locations.*

ing water need to be mobilized and put in place. There is a need for a systematic approach to pilot projects to learn what works best under different conditions.

Figure 4.3. *Numerous small conservation burn piles at the Big Chico Creek Ecological Reserve in Chico, California. The piles are extinguished by flinging the hot coals out onto the wet grass in wintertime. This also distributes and applies the biochar across the landscape. (Photo: WilsonBiochar.com)*

Figure 4.4. *Using a lid to snuff quench a flame-cap kiln. (Photo: WilsonBiochar.com)*

Summary of Engineering Challenges and Recommendations

1. We need to launch an effort to measure emissions from different kinds of kilns and conservation burn piles for several purposes: to demonstrate improvements compared to open burning to regulators; to aid in engineering cleaner and more efficient kiln designs; and to determine best practices for kiln operators and worker training.
2. We need to work with forestry professionals to develop better systems for kiln mobilization and deployment at scale across landscapes. Many different types of logging equipment and techniques can be adapted to the needs of on-site biochar production, whether it takes place in the woods or on a roadside or landing. We need access to knowledge and experience of forestry operators to help us design systems for different terrains and conditions.
3. We need to work with land managers to make sure that the techniques that we propose for processing slash materials into biochar are consistent with other economic and ecological management objectives. Where they are not, we need to go back to the drawing board and engineer more workable systems.
4. Ultimately, to expand biochar production to the landscape scale, we will need specifications and guidelines for the work that will allow managers to plan and offer contracts. These guidelines will also need to include workforce training objectives and safety protocols.

Economic Challenges

Background

The economies of indigenous cultures in the western hemisphere were to a large extent built on the expert use of landscape fires to manage resources in the absence of metal implements and draft animals (Pyne 1982). Large-scale landscape fires were used by Native Americans in western North America (and beyond) to maintain forage for the animals they hunted (Douglas 1914) as well as to promote the growth of staple crops such as camas, tarweed, biscuit root, huckleberries, and myriad other edible and medicinal plants (Riddle 1953; Anderson 1993).

Depending on their agro-ecological objectives, Native Americans burned habitats on one to five-year intervals (LaLande & Pullen 1999). This included the whole landscape—grasslands, shrublands and forest understories (Carloni 2005). These frequent, low intensity fires not only tipped the balance toward preferred plant and animal species, but also added regular pulses of char to the soil. With the extirpation of Indian management practices and the advent of effective fire suppression in the mid-20th century, this source of char input into our soils has dramatically decreased. Site-based biochar production can reverse this trend.

Every year in the forested areas of our nation, modern equipment and practices produce an enormous amount of small diameter, non-merchantable woody biomass during forest thinning and restoration activities. This highly flammable slash increases fire risk and restricts management options. The current practice in our region for disposing of this unmarketable woody material in areas where under-burning is not feasible is to build burn piles by hand and/or by machine, wait for them to dry, light them and walk away. While this may be the cheapest way to dispose of slash, open burn piles damage soils, produce significant amounts of smoke and greenhouse gases, and increase the risk of igniting wildfires downwind.

We have been developing an alternative practice to turn this liability into an asset by converting slash into biochar in the field. Fine fuels are used as feedstock for low-cost, transportable flame-cap kilns (see above) to heat the wood to high temperatures (450-550 °C) with little oxygen. This converts the slash to a form of carbonized biomass that when added to forest soils will remain sequestered there for centuries to millennia (Spokas 2010).

Biochar also increases soil water and nutrient storage capacity and promotes resilient soil ecosystems. Increased soil productivity promotes faster plant growth and the conversion of greenhouse gasses in the atmosphere into long-lasting biomass. Increased forest productivity also maintains and enhances biodiversity by accelerating the formation of old growth forest structure in appropriately configured stands.

Given the need to scale this technology out to reduce fire hazard, sequester carbon, and increase ecosystem productivity and resilience across the landscape, *on-site char production must become more competitive with current fuel treatments*.

Scope of Economic Challenges

While the extensive production and integration of biochar into local soils will have large-scale macroeconomic impacts (e.g., mitigating climate change, improving regional crop and timber yields, minimizing soil erosion and nutrient leaching, etc.), this discussion focuses on the microeconomic barriers to the wider acceptance of site-produced biochar as a mainstream practice. These challenges can be overcome in two ways: 1) by reducing the cost of producing biochar on site, and 2) by developing new markets for site-produced biochar.

Reducing the Cost of Biochar Production Compared to Open Pile Burning

The fewer times a piece of feedstock is handled, the less expensive it is to process. The first stage of producing biochar on site employs the same technologies, skills, and workforce as building burn piles, so there are well-trained local labor pools in regions where large amounts of woody biomass need to be treated. Feedstock handling for biochar production varies considerably with terrain and equipment, but typically requires more labor than simply piling and burning.

Current practice is to allow cut slash to dry in the field over the summer for fall charring. The piling necessary to dry the feedstock, and the subsequent dismantling of those piles before kiln loading, adds considerably to labor costs compared to simple hand piling and burning. If some of the extra touches could be eliminated by charring green feedstock, the cost of producing biochar in the field would come closer to the cost of hand piling and open burning treatments.

In order to test the efficacy of producing biochar directly from green feedstock, a project to compare logistics and biochar quality using green vs. dry feedstock was conducted on 12 acres at the Yew Creek Land Alliance property in southwest Oregon. Six acres of slash from an NRCS-funded oak habitat restoration project were dried in piles for the summer and were charred in the fall. On another six acres in the same project area, materials went directly from stump to kiln with feedstock four inches in diameter and below. Low-flammability woody residue over four inches was left on site as an ecosystem resource.

No quantitative measurements were made, but the consensus of the crew was that char recovery was at least as good with green feedstock as with dried feedstock, and with careful kiln loading, the increase in smoke was minimal (and presumably much of that was water vapor).

In a related pilot study, we found that 30% to 40% of the carbon contained in three green tons of feedstock charred in an insulated flame-cap kiln remained in the biochar. These results rival the highest recovery rates found in the literature. (See sidebar: *"Calculating Carbon Capture in Flame-Cap Kilns" on page 67*.)

Although we have demonstrated that streamlining the process by using green feedstock yielded robust biochar production, the potential for green biomass to produce potent greenhouse gases (GHGs) has yet to be rigorously measured. Given the amount of carbon trapped in the char, it is highly unlikely that GHG output of flame cap kilns approaches that of an open burn pile. Nonetheless, the types and amounts of emissions from both green and dry fuels need to be quantified to settle on best practices for future projects.

Another reason to collect quantitative data on kiln emissions is to demonstrate that flame-cap kilns produce significantly less smoke than open burning. This is visually obvious in practice, and empirically evident by observing how little char remains from open burn piles compared to slow pyrolysis in flame-cap kilns. Quantifying this smoke reduction may allow on site biochar producers to obtain burn permits when open burning is prohibited due to air quality considerations.

Incremental efficiencies can also be gained by looking into both new and old technologies for getting "stranded"[2] feedstock to the kilns and/or vice versa. This is particularly problematic in steep terrain in remote areas away from established road systems. A systematic evaluation of traditional and emerging technologies to augment human labor should be researched and compared to continue to improve best practices. For example, small tree yarding systems such as monocable ("zig-zag") systems developed in the 1970s and 1980s can be repurposed for on-site biochar production.

Developing New Markets for On-Site Biochar

Our sector of the industry integrates the production and use of biochar in the same location—biochar made on-site to be used on-site. The biochar we produce is rarely processed, marketed, transported, and sold. Rather, the value accrues to the landowner in the form of reduced fire danger, improved site productivity, reduced smoke production, and sequestered carbon. But because our char does not change hands, there is no monetary value attached to it. If integrated on-site biochar production is to become a significant practice, the "intangible" values of the char must be established to offset the extra production costs compared to open burning.

Two barriers exist to quantifying the value of biochar that has been returned to the soil: 1) quantitative data to determine the carbon sequestration efficiency and negative emissions of flame-cap kilns has been very limited with only one life cycle analysis study (Puettman et al. 2020), and 2) few if any studies have been done to establish the economic value of the ecosystem services provided by on-site biochar production.

While the value of standing biomass carbon in terms of CO_2 equivalents is well established for carbon offset markets, to date there have been no controlled studies of flame-cap kilns to determine feedstock C to biochar C efficiency ratios. Nor are there studies of avoided emissions relative to other methods of woody residue disposal. Until these parameters are established based on current equipment and practices, on-site biochar producers have no ability to capture the monetary value of their char. Once data on carbon sequestration rates and avoided emissions are gathered, a life cycle analysis of the alternate fates of a project's feedstock carbon can be used to generate the algorithms to quantify the ton of CO_2 equivalents stored in long-lasting biochar.

Although the value of the ecosystem services provided by integrated on-site biochar production is well-known, there is currently no system established to monetize these benefits in ways that generate income for the producer/landowner. Mechanisms

2 *Biomass that is currently unavailable due to access issues or the expense of harvest and transport.*

Calculating Carbon Capture in Flame-Cap Kilns

How much feedstock carbon becomes sequestered in biochar?

Preliminary results using green woody feedstock indicate that 30% to 40% of the carbon remains in the resulting char.

METHODS: We used an excavator to load a truck parked on a wireless scale *(top left/right)* to measure the green mass of our feedstock. A moisture meter was used to determine the mean moisture content of each species, and estimates were made of the percentages of each species in the feedstock.

Two burns *(bottom left)* were conducted on successive days—the first with approximately 1 ton of biomass, and the other with approximately 2 tons. The kilns were then snuffed for about 1 hour before being quenched with water to stop pyrolysis.

Three samples from each kiln were sent to a lab and analyzed for percent moisture, bulk density and percent carbon. We calculated biochar mass by measuring the char volume *(bottom right)* and multiplying by its bulk density.

RESULTS: Our preliminary results indicated that the first trial with approximately 1 ton of feedstock yielded 40% biochar carbon, and the second trial with approximately 2 tons yielded 30% biochar carbon.

CONCLUSIONS: Green feedstock can be successfully used to produce high-quality biochar with high conversion efficiency. ■

to generate income to the producer/landowner for these critical ecosystem services need to be developed. In addition to facilitating access to carbon markets, quantifying the value of on-site biochar production will also help to promote its use by landowners and land management agencies whose goals include outcomes beyond simple financial gain.

Once values are quantified for carbon sequestration, decreased emissions, and ecosystem services, standards can be developed and consulting foresters/ecologists/agronomists can be trained to certify the amount and quality of the biochar carbon stored on the site.

Summary of Economic Challenges

Current economic barriers to scaling out place-based biochar production include (but are not limited to):

1. Lack of comprehensive studies on traditional and emerging technologies to increase the efficiency of accessing stranded biomass and streamlining its conversion to biochar in the field.
2. Lack of rigorous measurements of green and dry feedstock to biochar carbon sequestration rates and avoided emissions compared to other fates for that biomass, allowing monetary value to be ascribed to these services.
3. Lack of data-based algorithms to access existing carbon markets.
4. Lack of studies to assign dollar values to the ecosystem services provided by in situ biochar production.

Ecological Challenges

Background

Ecological barriers include the lack of organized and easily available data about biochar's influence in forest ecosystems. This research is necessary to quantify the benefits of biochar and biochar production in comparison to other fuel reduction strategies. Addressing this barrier requires comprehensive and coordinated engagement with both forestry programs at regional universities as well as conservation and ecology organizations to create a comprehensive repository of research results on biochar's influence on forest ecology. Establishing this network of organized data will drive best practices in active forest management.

Understanding this influence requires both an understanding of biochar forestry research and challenges in modern forestry as the climate changes. One of the most significant challenges is wildfire, which is projected to increase with greater variation in weather patterns (Fried et al. 2004). These fires diminish the carbon capture capabilities of forests, while also contributing 4% to 6% of our nation's yearly GHG emissions. As increased public and private investment seeks to mitigate the risk of wildfires, quantifying the role of biochar in improving a forest's fire resilience offers an opportunity for scaled adoption at multiple scales.

The development of best practices for biochar re-application on the landscape should also be developed in coordination with Native American communities continuing their history of active fire management. As Native Americans have a long and rich tradition with prescribed burns, their knowledge can help shape best practices, and identify areas for further research. In this area of potential ecology collaboration, we seek to uplift voices not currently influencing modern forestry.

Scope of Ecological Challenges

Quantifying Reduction of Ecological Risk

Forests are expected to face an increasing number of environmental stressors in a changing climate, specifically issues of drought, flooding, soil erosion and nutrient depletion in topsoil, and pest damage. These factors combine to increase tree mortality, resulting in the increasing flammability of our woodlands. A combination of research and meta-analysis can help paint a picture of biochar's influence on these challenges, and quantify the reduction of these ecological risk factors.

Impact on Tree Growth Rate, Soil Health, and Forestry Economics

Quantifying the impact of biochar on tree growth requires a localized approach to research. Thomas & Gale (2015) found biochar amended forest soils to have varied effects on growth rates regionally and by tree species, with an average increase of 41%. Providing accurate and localized data that allows a landowner or logging company the ability to project the financial return can economically incentivize adoption. This research also needs to generate information on appropriate biochar application rates for different tree species, as well as the influence of soil health at different application rates.

Quantifying Impact on Fire Recovery

One key factor that could drive adoption is biochar's effects on resilience after fire. Quantifying the influence of biochar on forest ecosystem recovery, including plant and soil response, as well as post-fire challenges such as erosion, could help drive implementation. One study found that a biochar mulch reduced soil erosion by 50% to 64% compared to burned plots (Jien et al. 2013).

Carbon and Ecosystem Comparisons to Biomass Processing Alternatives
Comparing apples-to-apples data for on-site biochar production in comparison to other biomass processing alternatives gives research-based information to inform decision making. The factors guiding decision making should include impacts on ecological risk, but also carbon emissions and soil properties. For example, quantifying the biological health of soil after biochar production in comparison to soil sterilization from pile burning, and the subsequent vulnerability to invasive weeds, offers land managers a way to make informed decisions on their management practices.

On-Site Biochar Application Guidance
Organizations and landowners focused on returning biomass to the forest floor require clear guidance on the appropriate volume, size and distribution of biomass needed to provide the desired soil health, carbon sequestration and biological value, based on forest and soil types.

Biochar Integration with Prescribed Burning
As an increasing number of organizations look to integrate prescribed burning into forest management and fire risk reduction practices, there is potential for integrating biochar production. Several studies have estimated that the conversion rate of biomass to charcoal during a forest fire event ranges from 1% to 10% of the biomass consumed in a fire, or 1% to 2% of the biomass available in the forest (DeLuca & Aplet 2008). Some experimental burning practices have resulted in higher rates of biochar production, such as an experimental high-intensity crown fire in a Canadian boreal forest stand that captured 27.6% of the carbon in the fire zone in the form of charcoal. Aggregating the diverse number of metrics involved for biochar-based prescribed burns will likely require an open-source database, built collaboratively.

Summary of Ecological Challenges

1. Organized research on the benefits of place-based biochar in forest soils must center on the most pressing issues in modern forestry such as increasing resilience to wildfire, post-fire recovery, and increasing plant health in a changing climate.
2. Ecology research must quantify the carbon sequestration value of place-based biochar.
3. Potential exists to integrate place-based biochar with modern prescribed burning, requiring further research and outreach to practitioners.

Engagement/Education Challenges

Background

Biochar awareness, although growing, has not penetrated deeply into small-scale agriculture and forestry practices. In the past decade there has been noteworthy progress in the number and geographic distribution of workshops, demonstrations, and educational presentations increasing the general understanding about biochar efficacy, production and uses. But awareness has not yet converted learners to producers and consumers on the scale desired. The actual use of biochar in small agricultural and landscape-based forestry applications is still considered somewhat novel.

We find the highest acceptance and use levels among gardeners and niche farmers. Despite successes and enthusiasm amongst users in cannabis gardens, vineyards, orchards, and organic farms, markets remain small.

Forest managers who are looking for ways to improve operational efficacy, reduce carbon emissions, and improve forest health, are focusing more strongly than ever on the benefits of biochar (Figure 4.5 - 4.7). Taking their cue from nature and from indigenous traditional ecological knowledge and practices, forest managers understand that returning carbon to the soil in the form of charcoal provides a plethora of ecosystem values as well as socio-economic opportunities.

Figure 4.5. *Small private forest landowners attending a Family Forests stewardship presentation. Colville, Washington. 2018. (Photo: Gloria Flora)*

Figure 4.6. *Northeast Washington Forest Coalition and Colville National Forest personnel discuss forest health, 2018, Colville, Washington. (Photo: Gloria Flora)*

Figure 4.7. *The Tualatin Soil and Water Conservation District sponsored a two-day biochar workshop in 2019 at goat dairy that has an excess of waste woody biomass and a need for biochar to use in the goat barn. (Photo: WilsonBiochar.com)*

Scope of Engagement/ Education Challenges

Adoption Insights—Encouraging Change

Forestry operations and market farmers, because of ingrained practices and tight profit margins, are hesitant to change without being thoroughly convinced that that change will improve productivity and profit. Sustainable crop productivity improvement, soils remediation, drought protection, carbon sequestration and thus, improved long-term profit—some of biochar's outstanding benefits—are harder to see in immediate bottom lines.

Both forestry and agricultural practices generate biomass suitable for conversion to biochar. That includes surplus biomass which requires time and energy to manage. This provides an opportunity for on-site production and reduces cost-per-acre applications. However, suitable transportable equipment, basic skills for safe equipment operation, and user-friendly air quality permitting (should your operation be large or continuous enough to merit one) still require investment of time and money to get started.

Coordinating Education through Networks and Shared Resources

Fortunately, there is incredible depth of expertise, research, and applied science by biochar professionals around the globe. What is needed is a comprehensive, coordinated approach that provides easy access to that research, integrating it into diverse learning opportunities, workforce training, and technology transfer.

There are many high-quality biochar education programs and courses, but there is also a lack of consistency and language among them, even, for example, in defining, quantifying, and verifying the benefits of biochar. Coordination of these educational resources would increase efficacy, consistency, and availability of information for educators and presenters. Likewise, coordinated train-the-trainer programs would dramatically expand reach and could include opportunities for continuing education credits and other incentives.

Formal/semi-formal networks of practitioners are essential to provide training/leadership – as well as mutual assistance. Networking could likewise facilitate essential collaboration with organizations and agencies sharing a similar spectrum of objectives.

Target Audiences for Education

Increasing improved understanding of benefits and confidence in outcomes, in both the production and the use of biochar, requires increased coordination and a comprehensive approach to biochar education and outreach. Likewise, intelligent techniques that rely on integrating and improving current practices through minor modifications in biochar production processes, rather than adding work and expense, need to be fully explained, demonstrated, and proven in the field.

Key target audiences include agency leaders and large forest landowners who either make or influence decisions about forest management on specific landscapes. These entities would hire others to accomplish the work or train their own workforce in biomass handling for producing biochar. Other important groups are agencies and organizations with the mission to incentivize proper stewardship and educate the current and emerging generations of agricultural and small forest landowners (Figure 4.8). These landowners would most likely be doing the work themselves or with the assistance of small-scale contractors or individuals knowledgeable in the production of biochar. Forest and agricultural workers are yet another target audience, whether they are individual contractors or small companies providing services.

Figure 4.8. *Permaculturists and farmers learning biochar production and use at TerraFlora Permaculture Learning Center, 2019. Colville, Washington. (Photo: Gloria Flora)*

The final but very important audience are students: K-12, technical schools, through graduate school. Informal youth education organizations are also smart targets (e.g., 4-H, YMCA/YWCA, Future Farmers of America). Engaging the younger generation is one of the most significant ways to ensure that biochar and its benefits continue to be tested, refined, and replicated across landscapes.

Collaborating for Success

There are organizations at the international, national, regional, and local levels eager to participate in expanding biochar education and outreach. With the funding of key individuals, organizations, and initiatives in the four focus areas of engineering, economic, ecological and engagement/education, we believe significant strides can be made in increasing biochar education and outreach to grass-roots level audiences.

Because of the significant interest across educational venues, the opportunities for collaboration are high. Some tools are already developed, and contact lists from various agencies and organizations provide outreach avenues. Educational organizations are hungry for fresh opportunities and the latest techniques that provide integrated, natural solutions to address a range of issues.

Collaboration varies by location but is already occurring among the following groups since their mission and objectives overlap with the mission and objectives of biochar leaders:

- Agricultural commodity boards
- Community college vocational training programs
- Community gardens
- Economic development organizations
- Environmental NGOs
- Farmers
- Farmers' markets
- Federal agencies under U.S. Departments of Agriculture and the Interior
- Fire districts
- Professional society training programs
- Soil and water conservation districts
- State agencies (Departments of Natural Resources, Labor and Commerce)
- State firefighting services
- State park services
- Sustainable agriculture and permaculture NGOs
- Tribes
- University extension services
- Watershed councils

Summary of Engagement/ Education Challenges

We seek to provide comprehensive, consistent, and coordinated information disseminated through decentralized, yet broadly accessible, venues. These educational resources will cover small-scale, sustainable landscape-based production and use of biochar and will emphasize garden, farm, and forestry applications.

1. **A lack of well-developed biochar outreach and education networks.** Establishing networks and information clearinghouses for trainers to coordinate programs would increase consistency in information and techniques, and facilitate coordination with collaborators and partners. Training courses and educational materials should be widely accessible and broadened to reach to target audiences, particularly focused on on-line programs (entry, advanced, business, youth).

2. **Limited workforce training programs.** Labor-intensive forest management would have the local skill pool to implement wildfire risk, reduction, and restoration management projects which would in turn benefit small businesses, local economies, and individuals in collaboration with economic development organizations/agencies. Training programs would provide a missing link in public land forest management to biochar internships, potentially creating jobs and develop an emerging workforce in rural communities.
3. **Lack of business planning templates and cost estimation tools for contractors.** Accessible tools essential for small business should be developed in collaboration with Departments of Commerce and Secretaries of State, in addition to creating uniform sustainability guidelines for labor, carbon, and ecosystem services. Consistent permitting regulations and standardized cost ranges by forest habitat type, agricultural applications, etc. would facilitate communication between customer and provider, leading to greater interest in and implementation of biochar.
4. **No central database of research or clearinghouse for biochar-related information.** There is a need for comprehensive research syntheses and meta-analyses on biochar, collated by subject matter, geographic relevance, and application. This database would increase accessibility and usefulness of the myriad research while also differentiating between applied and theoretical studies. Not only would the database draw from and present academic papers, but traditional knowledge derived from historical practitioners would be included as well. The database would be used to curate and develop citizen science guides to be disseminated for individual projects or regional considerations. This distillation of complex data into accessible materials would benefit all biochar users.

RECOMMENDATIONS FOR IMPLEMENTING PLACE-BASED BIOCHAR

Our recommendations for implementation identify needs that are cross-cutting with impacts on each of the disciplines within our approach: Engineering, Economics, Ecology and Engagement. Investment in the following areas will have positive ripple-effects and impacts on other aspects of biochar production and use. Note that the numbering here does not indicate higher or lower priorities—all recommendations are interdependent and equally urgent.

1. **Fund research to quantify flame cap kiln biomass to biochar conversion efficiencies.** This will provide data to determine comparative design efficiencies and to quantify carbon sequestration rates for access to carbon markets.
2. **Fund research to quantify avoided emissions compared to conventional open burning.** This will provide data to access carbon markets, reduce health impacts, improve kiln effectiveness, and respond to air quality permitting concerns.
3. **Fund field research to compare different production systems for accessing stranded biomass in varying terrains.** Conduct a systematic study of traditional and emerging technologies to decrease feedstock handling and increase efficient kiln deployment in the field. This will establish best practices for maximizing biochar output and for providing economic metrics for contractors bidding on jobs.
4. **Evaluate carbon market potential.** Use kiln emissions, biochar conversion efficiency, and field production data to complete a life cycle analysis of the fates of feedstock carbon compared to current slash disposal methods. Establishing the market value of sequestered carbon and avoided emissions will allow contractors to offset the cost of creating biochar compared to open pile burning.
5. **Fund the development of business planning templates and cost estimation tools for contractors.** This will help practitioners doing projects at varying landscape scales to convert forest or agricultural residue into biochar. Include guidelines for labor, best production practices, and carbon and ecosystem benefits of biochar production. Determine contracting costs for greatest efficiency by collecting data on all contracting costs associated with on-site biochar production for comparison to other slash disposal pathways. Collaborate with departments of commerce and economic development agencies.
6. **Develop workforce training programs.** The Conservation Corps model offers an opportunity to address unemployment and underemployment while reconnecting people with their landscapes through collaboration with economic development organizations and community colleges. This work addresses fuels mitigation on public lands that is currently a missing link in wildfire risk reduction. These "Carbon Conservation Corps"

could offer the potential for certificate programs in landscape biochar technologies as a pathway to enter the natural resources, forestry, or arborist/urban landscaping sectors.

7. **Ascribe monetary value to the social and ecosystem services provided by place-based biochar production including:**
   - Smoke reduction and effects on human health,
   - Increase in forest resilience metrics to forest fires, drought and other risk factors in a changing climate, and
   - Impact on tree growth rates and forest soil health.
8. **Develop outreach and education networks.** These networks would enable place-based biochar practitioners to improve the quality and consistency of information, education, curricula and communication, including train-the-trainer and resource sharing programs. Targeted groups would include forest organizations, landowners, contractors, youth programs and indigenous practitioners of prescribed fire.
9. **Create an open access research and information clearinghouse for biochar producers at all scales.** A centralized online location for technical, ecological, and economic publications on biochar production, use, and influence on forests and farmland will allow researchers and organizations to merge data to collectively understand emerging opportunities from all sectors of the biochar industry.

CONCLUSIONS

Place-based biochar has the potential to solve many different problems centered on the diverse areas of forest health and management, climate change mitigation, and job creation. There are a legion of benefits resulting from increasing the health of our forests. Not only do forests provide products, they also provide clean air and water, wildlife habitat, and improved quality of life for residents who depend on these landscapes. Yet a warming climate threatens the ecological benefits of forests and increases the quantity and intensity of wildfires, endangering homes, businesses, and lives of individuals living in proximity to forests.

Converting forest slash from necessary vegetation management projects into biochar and leaving it on site to enrich forest soils should help forests become more resilient to the environmental stresses of climate change. The climate impact of place-based biochar is not limited to the soil carbon sequestration achieved by adding biochar. If biochar can be returned to forest soils at a large enough scale to improve soil and plant resiliency, it could be the difference between forests sequestering carbon or contributing carbon to the atmosphere through forest fires.

Solving climate change requires society-wide mobilization and focus. Place-based biochar provides a rare opportunity to achieve many additional social and economic benefits—healthy forests, fire protection and jobs—as we work to strengthen forest landscapes through the application of biochar.

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CHAPTER 5:

Moderate-Scale Biochar Production Across Forested Landscapes

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INTRODUCTION

Across the U.S., local communities, state, and federal agencies produce significant amounts of low-value forest biomass through wildfire risk reduction and forest health improvements. In California, for example, residues from thinning activities designed to reduce wildfire are estimated to be approximately 0.22 million tons annually in the forests of southern California and are expected to increase to 1,653 tons per day which is approximately 0.66 million tons annually for at least the next 20 years (Page-Dumroese et al. 2017a); potential biomass supply amounts increase with the increase of biomass market value (U.S. Department of Energy 2016). The One Billion Ton report indicates the potential for up to 368 million dry tons of forest wastes and residues that could be produced each year on a sustainable basis in the U.S. (Bufford & Neary 2010). There is an opportunity to build on these existing investments to create new economic and environmental benefits through the production of biochar.

This section describes barriers and strategies for significantly advancing moderate-scale biochar production specifically on available technologies that offer the potential to produce biochar at a reasonable price. *Moderate-scale biochar production* refers to relocatable biochar production systems converting 1,000-100,000 tons per year (TPY) of biomass to biochar at a rate of 300 lbs. of biochar output with one oven-dry cubic yard (CY) of biomass input. Technologies employ thermal conversion processes to covert biomass to biochar and are often relocatable and operate in or near forested landscapes. Operations at this scale involve some transport of biomass, typically at a distance less than 50 miles. An example of a moderate-scale biochar production system is shown in *Figure 5.1.* Relocatable biomass conversion technologies, at this scale, often integrate into existing business operations where biochar production is one of a suite of products. Forest residues (or biomass) are any woody biomass material or small-diameter whole trees that do not produce sawlogs, solid wood products, pulp or paper and are typically left on timber harvesting sites and piled at landings.

Figure 5.1. *Relocatable moderate-scale pyrolysis biochar system with a capacity of approximately one ton per hour of wood chips. (Photo: Jim Dooley)*

According to Grand View Research, Inc. (GVRI 2019) the global biochar market is expected to reach $3 billion by 2025. Biochar application in the agriculture community is expected to observe the fastest growth over the next nine years with an estimated compound annual growth rate (CAGR) of around 12.5% from 2018 to 2025. The global demand was 353.4 kilotons in 2017 and is expected to grow at a CAGR of 12.2% from 2018 to 2025. Agriculture has emerged as the largest application segment in 2017 and is estimated to generate revenue over $2,441.2 million by 2025; global demand for pyrolysis was $737 million in 2017 and is anticipated to witness staggered growth over the next nine years. North America was the dominant player in 2017 and accounted for 201 kilotons of biochar.

Increased demand for agricultural products and enhancement in crop yield and soil fertility drives a large part of the biochar market. Soil organic matter and, therefore, health is in decline across many ownerships due to various factors such as mining, deforestation, frequent use of chemical fertilizers, and aggressive agricultural practices. This negatively impacts the productivity of agricultural and forest products. However, biochar helps reduce nitrogen and phosphorus leaching into ground water, increases the ability of soil to retain water, moderates soil acidity, and boosts beneficial soil microbes. All these benefits, and a ready supply of woody biomass, make North America one of the largest markets for biochar.

In a 2018 survey of the U.S. biochar industry, Dovetail Partners Inc. concluded that the future of biochar industry was promising (Dovetail, Inc. 2018). Prior to this survey, the U.S. Biochar Initiative (USBI) estimated industry production to be between 15,000-20,000 TPY. The Dovetail survey supports production at a rate estimated at 35,000 to 70,000 TPY. Based on anecdotal input gathered at the 2018 USBI Biochar Conference about the production rates of some of the larger producers, even that estimate is probably conservative. However, for the purposes of this report the estimate of 45,000 TPY biochar will be used.

Moderate-scale biochar production occupies a distinct market niche and provides a valuable commercial foothold that can grow into broader economic and ecological impacts. This scale has seen recent technological developments. Entrepreneurs have deployed stand-alone relocatable technology as well as integrating on-site biochar production into forest products manufacturing businesses. Moderate-scale biochar production operations offer opportunities for increasing value (i.e., value added) to forest residues by converting them to biochar in the woods and increasing transportation efficiency by hauling processed products instead of low density, raw materials such as wood chips and hog fuel (Han et al. 2018). However, production rates and efficiencies for those technologies are still limited, requiring development of commercial technology and adjacent markets with minimal transportation costs.

Several companies have introduced moderate-scale technology and several businesses have integrated this equipment into their enterprises. Examples include Ag Energy Systems, Amaron Energy, Tigercat International, Inc. with the Carbonizer 500, and the forthcoming Air Curtain Inc. with the Char Boss. Further, moderate-scale production operations can be used to convert urban wood waste to biochar. This may be critically important after hurricanes, tornadoes, floods, or wildfire. Moderate-scale equipment is available at a lower capital expenditure ($50,000 - $2,000,000) and can be integrated into existing forest management and wood product manufacturing operations, as well as existing agricultural businesses, to supplement heating and cooling demands. Moderate-scale equipment is typically designed to be incrementally scaled up or down based on production or supply demand. Requirements for infrastructure and permits can be lessened as moderate-scale systems are movable. There are various technologies available to match biomass material types to produce custom or unique biochar products. Integration of the technology at this scale is critical because biochar currently often lacks sufficient value as a stand-alone product. A review on biochar production technologies can be found elsewhere (Garcia-Nunez et al. 2017) and are described further in *Chapter 11: Biochar Production*.

Moderate-scale biochar production systems require improved technology and feedstock preparations to improve the life cycle assessment (LCA) footprint and economics of production. Puettmann et al. (2019) performed a cradle-to-gate LCA to evaluate the environmental footprints from harvest to the thermochemical conversion of biomass into biochar and found that high quality "fixed carbon" was created when biochar was produced at higher temperatures. Feedstock quality such as moisture content and size variability had a direct impact on both biochar quality and biochar production efficiency. In-woods or near-the-forest operations also require a source of power to run relocatable biomass conversion technologies. While portable biomass gasifiers offer an option for on-site power generation and lower carbon emissions as compared to portable diesel generators, they can add additional costs to biochar production and may require different types of biomass feedstock from those used in other biochar production systems.

Restoration and fuel reduction thinning treatments often result in large quantities of slash, which is often burned in piles (Isaac & Hopkins 1937; McCulloch 1944; Dumroese et al. 2020). Pile burning is the preferred disposal method on many forest sites because it is an inexpensive way to reduce the volume of residues. Primary biochar uses include soil applications for agriculture, forestry, range, and mine reclamation. When biochar is matched to the soil and applied at appropriate rates, it can restore soil chemical, biological, and physical properties degraded from overuse, mismanagement, or natural disasters. Furthermore, it can remediate contamination of both organic and inorganic toxins. Biochar has a larger climate change mitigation potential than combustion of sustainably procured biomass for bioenergy by sequestering carbon below ground and reducing or avoiding greenhouse gas emissions (Woolf et al. 2010). However, long-term experiments must be carried out to uncover the mechanisms underlying soil process changes so key barriers that limit production and use of biochar can be addressed. These long-term experiments, coupled with education efforts, will make the use of biochar by the general public easier.

BARRIERS ASSOCIATED WITH MODERATE-SCALE BIOCHAR PRODUCTION

Economically viable biochar production at a moderate scale faces challenges at every phase of the operation. Moderate-scale relocatable operations often deal with biomass that has little value and therefore there is a need to recover revenues from biochar production (i.e., costs are greater than revenues), whether as a stand-alone product or integrated into a larger operation. Technology available at a moderate scale usually lacks sophisticated controls that allow manipulation of temperature, residence time, and other production factors. These limitations may constrain the functional values and applicability of the resulting biochar. Furthermore, it is important to commercialize biochar products through development of product standards and successful business models. Lack of market development and policy support have been often cited as key barriers to biochar entrepreneurship efforts. Moderate-scale biochar production units offer, however, the opportunity to control processing conditions to produce engineered chars with targeted properties.

Product Development

States vary in their requirements for biochar standards. Most states treat biochar as a soil amendment because it can improve the soil's physical, chemical, and biological properties. Biochar can be labeled as a fertilizer, but it must be tested, and nutrient content defined. Further, the Association of American Plant Food Control Officials (AAPFCO) requires a 60% minimum carbon content. This may cause problems as several moderate-scale production methods may produce biochar with a carbon content less than 60%. However, the United States Department of Agriculture (USDA) defines biochar used as a soil amendment as having a threshold of 25% carbon.

Testing by producers will be critical for allowing potential customers to fully understand biochar properties including carbon content, pH, porosity, nutrients, and heavy metals. Once tested, biochar can be used for many products. For example, there are numerous contaminants in wastewater that can be filtered out using biochar (e.g., phosphate). Similarly, there are numerous agronomic uses for biochar that increase soil or animal health, increase crop production, or reduce runoff (see *Chapter 8: Agricultural Use*). However, the feedstock used for biochar production (e.g., hardwood, softwood, invasive woody plants) and the production process will determine biochar efficacy in specific soil types. Therefore, small, in-field testing pilot projects are the key to determining where and when biochar can be most effective and should be followed-up with long-term tests in forest, range, agriculture, and mine lands.

Clear standards and specifications for biochar products would allow the private sector to promote consistent products that have adequate labeling for safe use as a soil amendment or fertilizer. This is not a concern if the biochar is created and used on-site with the only goal being carbon sequestration. However, if the biochar is to be used on forest-adjacent soils for crop production, animal bedding, or in a compost it is critical to understand how the biochar was made and if it will be used as a fertilizer or soil amendment (USBI 2019).

Business Development

Absent a lucrative price on carbon, the business development and deployment of biochar requires commercialization based on known benefits. While moderate-scale biochar has seen notable independent technology and enterprise advancements, an interrelated set of barriers hinder development of a successful business.

Foremost, the commercialization of moderate-scale biochar businesses presents significant risk and opportunities, as it allows changing operational conditions required to produce different types of biochar for targeted properties. Unlike other estab-

Table 5.1. *Costs and capacities of moderate scale biochar production technologies. (modified from Delaney & Miles 2019)*

Type	Scale	Suppliers	Wood Fuel Input Form	Capacity (tons in/hr)	Biomass (tons in/yr)	Biochar/ Feedstock (%)	Biochar (tons/8 hr day)	Biochar (tons/240 day yr)	Capital Cost
Relocatable	Medium	Pyreg, Pyrocal	Chips	2	3,840	25	4	960	$1.5-$2M
Relocatable	Medium	Air curtain burners (ROI Equipment)	Bulky fuel	3	5,760	7.5	1.8	432	$485K

lished industries, public acceptance and assistance to mitigate the risks of biochar business operations are at an early stage and relatively limited. For example, the type of large-scale research and development projects that helped commercialize biomass to jet fuel or mass timber construction have not appeared in the biochar space. From a practical perspective, this leaves entrepreneurs to shoulder the bulk of the risk, which in turn limits the pace of commercialization.

Similarly, technical assistance programs to support entrepreneurs are also relatively lacking across all scales of biochar development. This is due in large part to the nascent nature of the biochar space as targeted technical assistance programs have yet to be developed. Strong technical expertise exists; however, it is not widely available. For example, county level extension agents are available to provide technical assistance on topics ranging from forestry to gardening to food preservation, but usually not biochar.

Lastly, moderate-scale biochar development faces the challenge of high transportation cost relative to product value. Access to biochar product markets in a reasonable distance (e.g., less than 100 miles) is important for a successful business operation. This is especially true if the scale of daily biochar production is "moderate." In addition, low product values further limit product sales to regional markets. On the production side, high feedstock procurement costs will critically decrease the feasibility of a moderate-scale biochar production operation. Optimal operational logistics connecting in-woods biochar production and feedstock supply are still a new concept and have not been well practiced yet.

Technology Development

Several moderate-scale biochar production technologies are available currently, but high biochar production costs make it difficult to be economically feasible. There have been techno-economic analyses conducted in the last several years (Campbell et al. 2018; Sahoo et al. 2019; Garcia-Nunez et al. 2017).

In 2018, a review of available biochar production technologies at moderate scales for a juniper (*Juniperus* spp.) control project in Oregon was conducted (Delaney & Miles 2019). At that time, capital costs ranged from $500,000 to about $2,000,000 (Table 5.1).

In 2018, the 'break-even' price point needed for biochar was about $600 per ton in off-site markets. However, it required a cost-share contribution from federal agencies to clear the juniper (i.e., providing the biomass feedstocks). At prices of about $800 per ton biochar, combined with the Natural Resources Conservation Service (NRCS) cost share, starts to become profitable (Figure 5.2). Costs and capacities of moderate-scale biochar production technologies. (Delaney & Miles 2019).

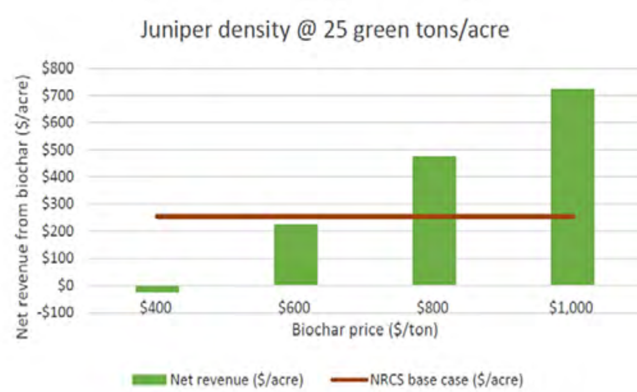

Figure 5.2. *Costs and capacities of moderate scale biochar production technologies. (Delaney & Miles 2019)*

Since 2018, other moderate-scale technologies such as Artichar (Iowa) and Organilock (Kentucky) have entered the market as part of effort to produce biochar as a profitable business. These technologies are being evaluated in a new techno-economic analysis for a current biomass-biochar project in Nebraska, with results not yet available at the time of publication. Availability of low-cost, moderate-scale biochar production technologies is still lacking, making it difficult to increase biochar production at or near the forest.

Market Development

The customers and consumers of biochar fall into a number of segments (classifications). Retail consumers and landscapers that maintain residential gardens tend to be well-informed about soil amendments and their value. However, there is little evidence that common information sources (e.g., gardening books, gardening TV shows, garden columns in newspapers and online) cover biochar as a plausible or beneficial soil amendment. A limited survey of retail nurseries and big-box home improvement stores in the Seattle area found that none carried biochar or blended soil amendments claiming to include biochar, even though such products exist, as shown in Figure 5.3.

Figure 5.3. *Example of retail biochar soil amendment product. (Photo: Lowes.com)*

The willingness-to-pay for biochar products will remain flat unless consumer awareness rises. Comparing biochar to other soil amendments would yield some insights about market potential. Biochar is a direct replacement for vermiculite in potting soil mixes to provide aeration and water holding. With vermiculite selling at retail for $503 per CY ($4.98 per 8 qt. bag; Table 5.2), it is quite plausible to produce biochar in 2 cubic foot packages to compete directly with vermiculite. Although Seneca Farm biochar is not available at businesses contacted in the Seattle market, it sells online for more than $3,800 per CY in retail packages.

Table 5.2. *Retail prices for soil amendments in Seattle June 1, 2020.*

Soil Amendment	Retail Volume (ft^3)	Retail ($)	$/$ft^3$	$/$yd^3$
Steer manure mix	1	$2.28	$2.28	$62
Promix medium	2.2	$6.24	$2.84	$77
Greenmix	1.5	$4.28	$2.85	$77
Mushroom compost	1	$4.28	$4.28	$116
Chicken manure mix	1	$4.48	$4.48	$121
Compost	1	$5.18	$5.18	$140
Peat moss	2	$11.98	$5.99	$162
Vermiculite	0.3	$4.98	$18.63	$503
Seneca Farms Biochar	0.3	$42.00	$142.80	$3,856

Retail markets and consumers need wide-scale education about biochar in comparison to other soil amendments—a basis for comparing values and setting a fair retail price point. Other soil amendment customers include public agencies, urban renewal districts, parks, golf courses, commercial gardens, organic farmers, and sustainable agriculture. These customers also need to better understand product availability, appropriate packaging (supersacks and bulk), and fair pricing. Commodity boards (e.g., almonds, wine grapes) have expressed interest in biochar and working through them to educate their constituents is an important strategy.

Regulatory Permitting and Mitigation

Entrepreneurs or communities seeking to deploy moderate-scale biochar technologies face significant challenges acquiring state air quality permits. Current state level instruments are either cost prohibitive, excessively arduous, or both. The current regulatory approach often treats relocatable technology as a point source polluter, which requires a Title V air quality discharge permit (USEPA 2021). Unfortunately, the regulatory framework does not recognize the air quality benefits of using air curtain burners or other relocatable biochar technology to dispose of slash piles as compared to open air burning. In general, combustion in an air curtain burner results in considerably lower emissions of particulate matter and carbon dioxide (CO_2) as compared with open pile burning (Miller & Lemieux 2012), but feedstock type, moisture content, and equipment parameters can make the emissions quite variable. Moderate-scale biochar production can be a clean production technology, but some units may require additional emission controls to meet state or local standards. In general, moderate-scale equipment is environmentally sound and produces less greenhouse gas emissions than composting, combustion for energy, wildfires, or slash pile burning (Sahoo et al. 2019). For more information, see *Chapter 12: Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems*.

STRATEGIES TO SUBSTANTIVELY INCREASE MODERATE-SCALE BIOCHAR PRODUCTION

Moderate-scale biochar production has achieved some commercial viability both as an integrated product or service as a stand-alone product. When integrated into an existing service, biochar is often produced as a byproduct of biomass disposal or combustion. Similarly, biochar can complement other products produced at an integrated wood products facility.

The strategy for growing moderate-scale biochar production aims to expand existing market opportunities while positioning the segment to participate in sector-wide opportunities, such as carbon sequestration. Using forest biomass as feedstock for biochar production could contribute to decreased wildfire risk. Applying biochar to soils would provide benefits to forest, range, agricultural, or mine soils, or for other agronomic purposes (e.g., animal bedding). We suggest the following specific strategies in the areas of market development, product development, technology development, business development support, and regulatory reform to make moderate-scale biochar production operations successful:

Market Development

- Collaborate across the biochar industry to design protocols and procedures that monetize the carbon value for moderate-scaled biochar production from woody biomass.
- Conduct a survey to define the current limitations and barriers to incentivizing biochar use and markets on several fronts. This survey could include a wide variety of stakeholders involved in the biochar production and end use chain.
- Build enhanced customer awareness and drive demand by conducting a marketing and customer awareness campaign to encourage retail presence in 80% of retail nurseries and garden centers in the region, and a similar one directed to consumers nationwide.
- Engage with community-based fuels reduction and forest management effort to integrate biochar production and use into local efforts.
- Connect wildland-urban interface and other forest sites with urban forest sites that provide distributed enterprises.

Product Development

- Diversify the number of products that can be obtained from amorphous carbons (e.g., construction materials, catalysts, adsorbents, food additives, capacitors, soil amendments).
- Create clear standards and specifications for moderate-scale biochar production to promote uniform products that have adequate labeling for safe use as a soil amendment or fertilizer. Engage with agricultural departments as requirements for biochar standards vary across the region.
- Develop clear biochar use specifications to foster biochar demand from public agencies and public landowners.
- Complete product testing with producers to allow potential customers to understand biochar properties including pH, porosity, nutrients, and heavy metal content.
- Promote and develop research funding for advanced carbon-based materials.

Technology Development

- Improve the performance and value of biochar production technologies through targeted research partnerships.
- Conduct robust techno-economic analysis on moderate-scale biochar production operations to identify factors affecting economic viability.
- Demonstrate efficacy of integrated biochar combined heat and power applications.
- Develop technologies to produce higher value carbon-based engineered materials.
- Develop better technologies and systems for biomass handling, transport, drying, and size reduction (e.g., chipping and chunking).

Business Development Support

- Provide comprehensive business development resources to entrepreneurs and their partners to

- foster business expansion and diversification. Services would include targeted technical assistance, research partnerships, access to capital and regulatory support.
- Communicate the impacts, benefits, and potential of successful public-private partnerships.

Regulatory Reform

- Develop a public-private partnership with the regulatory community to create permitting instruments commensurate with the relocatable nature of emerging technology platforms.
- Conduct additional life cycle assessments to determine greenhouse gas intensities and carbon sequestration potential of various biochar production technologies.
- Establish best management practices for biochar use in stormwater management, tree-planting, composting, manure management, food waste composting, mine land reclamation, and other uses in environmental management and remediation.

EXAMPLES OF SCENARIOS ILLUSTRATING MODERATE-SCALE BIOCHAR PRODUCTION INDUSTRY DEVELOPMENT

In this section, we illustrate several scenarios of more complete moderate scale biochar enterprises than exist today. The first scenario discusses how functionalized biochar responds to the needs of specific applications in water quality, agriculture, forestry, carbon sequestration, and other uses. Most of these applications demand that the energy and carbon balances be managed to achieve policy or carbon market objectives as well as functional performance. A second scenario capitalizes on highly distributed production by entrepreneurs through centralized aggregation and marketing. The third scenario offers a larger scale in-woods biochar production scheme for direct use of the resulting biochar in the immediate area of production.

Scenario 1: Highly Functional Biochar from Highly Efficient Production Systems

This scenario uses moderate-scale pyrolysis systems to produce functionalized biochar products from woody biomass. It seeks to approach the minimum theoretical energy consumption and maximize the theoretical stable carbon content while closing the materials and energy balance for the entire production system from biomass collection through delivery to a centralized distribution center. At least in theory, biochar yields as high as 50% of the original feedstock mass (Mohan et al. 2006) are possible when the stable carbon content is within the USDA guidelines (Klinar 2016). The biochar production system may be located at a large (two to five acres) landing within a forest or at a distributed location as close to the wood source as practical. It is expected that a production system will be moved only every few weeks to few months. Some may never move if they are located in communities surrounded by actively managed forests. This scenario combines distributed primary production of biochar using highly technical systems with centralized packaging, distribution, and marketing of products from many producers.

Consumption of fossil fuel can be minimized during biomass collection by gathering woody biomass essentially intact and achieving high transport payloads by bundling or baling. Instead of chipping or grinding to produce efficient pyrolysis feedstocks, the materials would be crushed using rollers into scrim (long strands) having a mean strand thickness of less than 0.24 in. (6mm). The scrim may be cross sheared to shorter, more flowable particles using a rotary shear machine (Dooley et al. 2011). A screening system will redirect oversize materials to be re-crushed and recut, and fines, which contain high levels of soil, will be stockpiled for use as mulch.

Drying is likely to be needed prior to pyrolysis. The drying energy will be delivered from a) exhaust gases from the pyrolyzer, and b) direct fired heating with gas supplied by an on-site gasifier. A major innovation in the dryer will be a capability to condense water vapor from the exhaust to use in the biochar quenching process. Condensed vapor may pass through a membrane filter so that terpenes (organic compounds produced by conifers that have desirable properties for various industrial uses) and other compounds may be recovered as co-products.

The pyrolyzer will include a number of advanced features to maximize stable carbon content, enable rapid changes in feedstock particle sizes, and adjust reactor temperature to produce biochars having particular market matches. Although the pyrolyzer will operate continuously, feedstock and temperature changes will create end-to-end batches of biochar. Individual batches could have an infeed particle size ranging from 0.08-0.39 in. (2-10 mm) and temperatures ranging from 842-1,472 ºF (450-800 ºC). In some cases, the feedstock may be mixed or sprayed with functionalizing agents at the infeed of the pyrolyzer, so they become bound with the biochar matrix during conversion. Likewise, functionalizing agents, including pyrolytic acid if wanted, can be added to the biochar quenching water. Each pyrolyzer would consume 1-5 tons of woody biomass per hour and produce 3-16 CY of biochar per hour.

After cooling, biochar will be packaged in supersacks or loaded into bulk trucks or hook lift containers for transport to a centralized final processing, packaging, and distribution warehouse. Each warehouse may receive biochar from a coordinated regional network of production systems.

Scenario 2: Biochar as a Specialty Forest Product – Aggregated Biochar Upgraded from Gate-Char

This scenario enables small- and moderate-scale entities to produce biochar using any method they choose. Micro-producers may use backyard kilns and piles, while others may use in-woods burn piles, kilns, or air-curtain burners. “Gate-char” is bulk biochar purchased by a biochar aggregator or distributor from independent, typically small producers based on the quality and quantity delivered on an ad hoc basis (Figure 5.4). Gate-char gathered from potentially hundreds of producers in a region would be characterized, sorted, upgraded if needed, packaged, distributed, and marketed for the benefit of all. This scenario decouples biochar production from quality management, packaging, marketing, and sales. Decoupling production from sales maximizes the number of people can become engaged in gathering and converting woody biomass to biochar. Their income would be a function of biochar volume and attributes at the point where it is scaled and assayed at the gate of a buyer. Examples of commodity biochar uses include soil amendment on disturbed land, and to improve water holding capacity of arid sites. At the other end of the spectrum are technical biochars produced at high temperature that are useful for water treatment applications.

Figure 5.4. *Gate-char can be composted with manure, soil, or other organic material to create a higher-value product. (Photo: USDA Forest Service)*

This system may be inefficient in carbon, emissions, and labor on the production side of the scenario. However, it provides a vehicle for many producers with wide ranging motives to participate in the market without having to sell, bill, ship, etc. A distributed system would engage citizens in production and spur interest across communities about the connections among woody biomass, biochar, and soil health.

Biochar aggregators would operate much like, and often be, the same firms in many communities that currently deal in berries, bear grass, wreaths in the fall, mushrooms, and other forest specialty products. The specialty forest products industry has not to-date been involved in biochar for unknown reasons. However, biochar may fit well as a boutique product to sell through many of the same outlets as other non-food specialty forest products.

In order for this type of aggregator industry segment to become established, information and training is needed about biochar quality attributes, mapping of biochar types to uses, and broad consumer education to increase awareness of biochar. More sophisticated aggregators are likely to have their own thermal reprocessing, grinders, screens, functionalizing systems, and other equipment to enable gate-char upgrading to high value filtration media, soil amendment for heavy-metals contaminated sites, fish aquarium filter media, etc. They are likely also to have X-ray diffraction, hyperspectral imaging, high performance liquid chromatography (HPLC) or other laboratory methods to value or certify (on labels) the stable carbon content of products.

Scenario 3: Remote Forest Biochar Production Research and Immediate In-Woods Utilization

We propose that the creation of Remote Forest Research Stations (RFRS) to examine the benefits and realities of biochar production for use in the woods would be an excellent investment for the U.S. to make for the benefit of its citizens. Funding for this program would be used to establish remote research camps across the US, in collaboration with universities, existing Federal researchers (e.g., USDA Agricultural Research Service (ARS), Forest Service (USFS), NRCS, non-governmental organizations (NGOs), and for-profit companies.

Throughout the U.S., state and federal agencies are spending millions of dollars to reduce wildfire risk on forestlands. Examples include the USDA NRCS (Regional Conservation Partnership Program (RCPP)) and the USDA USFS Collaborative Forest Landscape Restoration Program (CFLRP). These projects produce thousands of tons of low-value forest biomass in remote areas each year. We believe there is an opportunity to build on these existing wildfire risk reduction investments to create new economic and environmental benefits through the production of biochar. The concept is to gather excess forest biomass in remote regions (fuel load reduction), convert it to biochar, and then use the material to help solve remote environmental issues while also creating new job and training opportunities for American workers. The camps would be located where there are existing wildfire fuels reduction efforts already underway. These RFRSs would be proving grounds, for not just the biochar production technology, but for the investigation of the use of the material to benefit the local ecosystem and economy.

The U.S. has a legacy of both organic and inorganic toxins left from mining operations in our national forests. There are also numerous non-toxic mine sites with no soil or vegetation. Imagine if we went to one of these headwaters where there are vast amounts of forest fuel loads just waiting to cause a devastating fire, and instead we turned that fuel load into biochar for remediation of both mine site and overstocked watershed. What would that mean for the downstream communities? Work like this can provide local jobs, a revitalized environment, healthy water, decreased erosion, and fire risk mitigation, just to name a few benefits.

Project Example: Using Biochar to Mitigate Pollution Near Headwater Streams

About 40% of headwater streams in western rivers are polluted with discharges from abandoned mines. Pollutants discharged into waterways from abandoned mines include arsenic (As), cadmium (Cd), copper (Cu), and zinc (Zn) (Rodriguez-Franco & Page-Dumroese 2021). Outside of the community of Riddle in southern Oregon, a research project is underway to test if biochar can help mitigate pollution at Formosa Mine. This area also has high forest fuel loads and is at risk of severe wildfires. The communities in southern Oregon are actively trying to reduce wildfire risk and fear their towns "will become the next Paradise, California" (e.g., Camp Fire). In 2007, the U.S. Environmental Protection Agency (EPA) added the Formosa Mine to the National Priorities List and designated it as a Superfund site. The mine operated as a copper and zinc mine from 1910 to 1937.

Figure 5.5. *Researchers test whether the addition of biochar helps establish vegetation at the Formosa mine site in Riddle, Oregon. (Photo: Kristin Trippe)*

There are two main sources of environmental pollution at the Formosa Mine site. The first, acid mine drainage, is contaminating surface and subsurface waters in the area and has severely degraded 17 miles of Middle Creek and the South Fork of Middle Creek, affecting macroinvertebrates, resident fish, coastal steelhead trout, and Oregon coastal Coho salmon (EPA 2016). The second, wind and water erosion, is due to a lack of vegetative cover on the exposed and degraded land and moves contaminated soil off-site. This site has highly acidic, heavy metal-laden soils, which limit establishment of a soil-stabilizing plant cover. Additionally, plant establishment is challenging because many abandoned mines are in dry areas that lack precipitation, are on steeply sloping, exposed positions in the landscape, or have coarse textured soils with poor water retention. Actions are needed to adjust soil pH, reduce metal concentrations, and improve water-holding characteristics (Novak et al. 2016). For the last couple of years, researchers have been testing if biochar amendments can help establish vegetative cover at the Formosa Mine (Figure 5.5). This project builds on the results and experiences of researchers and expands the effort by EPA to revegetate the site. Additional research should be directed to using biochar to filter water, mitigate acid mine pollution, and reduce impacts on nearby fish bearing streams and rivers.

ECOSYSTEM IMPACTS AND BENEFITS FROM PRODUCTION AND APPLICATION OF BIOCHAR – MODERATE-SCALE BIOCHAR PRODUCTION

Often forest residues (tops, limbs, unmerchantable material) generated from forest harvest and restoration operations in the western U.S. are burned in slash piles to reduce wood volume (Isaac & Hopkins 1937; McCulloch 1944). However, this type of wood disposal can alter soil physical, chemical, and biological properties, seed reserves, and plant tissues (Certini 2005). Biochar created from woody biomass has a high carbon to nitrogen ratio (ranging from 100-700:1) which means it is carbon rich and an excellent tool for carbon sequestration. As noted in the scenarios, moderate-scale biochar production (e.g., Tigercat Carbonizer, Air Burner, Inc., BurnBoss, CharBoss) in-woods or near woods can convert this woody biomass to biochar where it can be used for forest, range, agricultural, or mine soil restoration while improving forest health and reducing wildfire risk. Further, moderate-scale production operations can be used to convert urban wood waste to biochar which is critically important after hurricanes, tornadoes, floods, or wildfire. The technology at the moderate scale is available at a lower capital expenditure ($50,000-$2,000,000) than large-scale production facilities and the work can be integrated into existing logging business operations or at sawmills. Integration of the technology at this scale is critical because biochar currently does not have sufficient value.

In order to re-think the benefits of using woody biomass for biochar production, consider that for the USDA USFS, fuel reduction treatments can cost over $6,000 per acre and this activity produces little benefit for the community if the wood cannot be sold. If the wood were converted to biochar and sold, it can be a source of income for the USFS, create jobs in rural communities, sequester carbon belowground, and improve soil health. Biochar may also be a way to store more water within the soil profile, thereby limiting runoff, erosion, and water pollution. Back of the envelope calculations (Jim Archuleta, USFS Region 6, personal communication) indicate that to increase soil organic matter by 1% on an acre of ground, approximately 10-12 tons of biochar would be needed. In addition, there are 12 million acres of dryland farming in the Pacific Northwest where biochar could be used, resulting in the need for approximately 144 million tons of biochar. Since the conversion rate of biomass to biochar is usually less than or equal to 50%, more than 290 million tons of biomass would be needed.

Conversion to biochar rather than pile burning also offers a way to reduce emissions and fire risk while improving the health of forests and soil. We note in the Market Development section that biochar marketing as a garden, landscape, or golf course turfgrass amendment should be pursued. These activities all take place in the public sphere where biochar use and benefits can be highlighted. This raises the awareness of biochar technology and can improve acceptability. If biochar was only used as a carbon sequestration tool, then using it in road construction or under buildings could be considered. The properties of biochar vary greatly depending on feedstock and pyrolysis conditions, but the application of a high carbon substrate to forest, range, urban, agricultural, and mine soils can provide a wide array of ecosystem services. Further, moderate-scale production equipment offers a method of conversion that uses non-valued wood and creates a marketable product.

Figure 5.6. *This forest road is to be permanently deactivated after completion of timber harvest operations near Humboldt, California. (Photo: Han-Sup Han)*

Figure 5.7. *Forest road near Humboldt, California that has been decommissioned and revegetated to reduce soil erosion. (Photo: Han-Sup Han)*

Forest Roads

Forest roads are essential for forest management, particularly thinning activities. Roads are usually built to provide access to timber resources, but also for public access. However, many forest roads no longer meet the standards for safety and environmental protection and are, therefore, decommissioned (Figure 5.6). The decommissioning effort is done to stabilize and restore the unneeded roads to a natural state (Figure 5.7). Often these highly compacted roadways are difficult to restore, lack water holding capacity, and often host invasive species (Page-Dumroese et al. 2017b). Biochar, created on- or near-site, can increase soil water by as much as 26% (Ramlow et al. 2018) and decrease invasive species (Page-Dumroese et al. 2017b). Further, biochar used in strips near roads and waterways could be one way to remove nutrients or other pollutants before runoff reaches a stream.

Abandoned Mine Lands

As noted in Scenario 3, mine tailings, waste rock piles, and acid mine drainage are legacies of hardrock mining in the western U.S. Many of these sites are within or near national forest boundaries and are also near available woody biomass for biochar production. The mine features contribute to mineralized soil, water acidification, and erosion due to the lack of vegetative cover; soil remediation to reduce contamination is critical. Each degraded or contaminated area is unique and will require some biochar testing to determine what might work best (e.g., biochar pH, porosity, cation exchange capacity). However, the addition of biochar to highly weathered acidic soil can influence seed germination, plant growth, vegetation cover, and nitrogen and phosphorus use efficiency (Zhu et al. 2014; Page-Dumroese et al. 2018). In addition, material such as wood chips, wood strands, or biosolids can be added to increase soil moisture and protect germinating seeds (Figure 5.8).

Greenhouse Gas Emissions

Application of biochar to soil has the potential to improve soil nutrient and water holding capacity and sustainably store carbon, thereby reducing greenhouse gas emissions (Verheijen et al. 2010). In the inland northwest, biochar, applied at a rate of 0, 1, or 11 tons per acre to forest soil had no impact on the flux of CO_2 or methane (CH_4), and nitrous oxide (NO) was at an undetectable level. However, biochar additions did increase soil carbon by as much as 41%, making it a useful tool for climate change mitigation (Sarauer et al. 2018). Biochar has been shown to enhance cereal crop production while simultaneously decreasing greenhouse gas emissions, but on forest or range sites there are only a few documented concomitant increases in stand productivity. In a meta-analysis of biochar use in forest restoration, tree seedlings do respond to biochar additions (Thomas & Gale 2015).

POLICIES AND REGULATIONS ENCOURAGING BIOCHAR PRODUCTION AND UTILIZATION

Given the presence of potential pollutants and the diversity of feedstocks used to produce biochar, its characterization for a particular application is essential

Figure 5.8. *Installation of mine site restoration treatments on the Umatilla National Forest near a newly restored stream near the Granite Gold District which had been dredged for gold throughout the 19th and 20th centuries. The rock tailing piles near the stream were flattened and capped with silt loam in the 1970's, but little vegetation had developed. Treatments were wood chips, biochar, and biosolids. (Photo: USDA Forest Service)*

to optimize its use. According to Burns et al. (2014) one consideration, in terms of biochar cost, is whether or not there are regulations on biomass, whether biochar would be deemed a waste material, and how that influences its use as a soil amendment. This may require further research to construct appropriate public policy designed to regulate biochar production and management and no such regulations exist in the U.S.

One concern for biochar use has been the potential for contamination with organic or inorganic toxins created or enhanced during the pyrolysis process. In the US, biochar producers have to follow federal and state air quality regulations for polycyclic aromatic hydrocarbons (PAHs) and other pollutants. The EPA, under the Emergency Planning and Community Right-to-Know Act of 1986 (EPCRA), requires certain facilities manufacturing, processing, or otherwise using listed toxic chemicals to report the annual quantity of such chemicals entering each environmental medium. Such facilities must also report pollution prevention and recycling data for such chemicals, pursuant to Section 6607 of the Pollution Prevention Act, 42 U.S.C. 13106. When enacted, EPCRA Section 313 established an initial list of toxic chemicals that was comprised of more than 300 chemicals and 20 chemical categories. EPCRA Section 313(d) authorized EPA to add chemicals to or delete chemicals from the list and sets forth criteria for these actions. EPCRA Section 313 currently requires reporting on over 600 chemicals and chemical categories. The list of PAHs regulated by EPA was released in 2008. However, Garcia-Perez et al. (2011) note that PAHs and dioxins/furans were in such low concentrations in biochar that they pose no human health or environmental hazards. Garcia-Perez et al. concluded that it is possible to produce biochar with concentrations of PAHs and dioxins/furans several times lower than current clean up levels required under the Model Toxic Control Act, Chapter 70.105D RCW. In Washington State, concentrations of dioxins measured in biochar were close to those reported for soil background levels.

In 2016 the Association of American Plant Food Control Officials (AAPFCO), which is a membership organization of state and provincial Departments of Agriculture covering the U.S. and Canada, worked to get consensus and develop models for legislation, analysis, standards, labeling and safe use of feed, fertilizer and soil amendments and approved a standard for labeling biochar (Draper 2019). Currently, 38 states have regulations related to soil amendments in general; however, to date, few have officially adopted specific regulation related to biochar. More states adopting biochar and recognizing its utility for a variety of applications will be key to encourage biochar use. One exception to listing biochar in regulations is the California Department of Food and Agriculture (CDFA) which adopted the AAPFCO biochar definition in full. This means that biochar producers selling biochar that meets the 60% carbon minimum standard must register their product through their state's Department of Agriculture. Other states, such as Washington, may adjust the AAPFCO definition slightly to include heavy metal thresholds. Failure to register labels with the relevant state Department of Agriculture may result in products being pulled from shelves. Consideration of the USDA carbon standard (25%) for a soil amendment is also needed when these adjustments are conducted at the state level (Draper 2019).

Biochar awareness is increasing in the U.S. and according to Draper (2019) biochar producers are registering in the voluntary BioPreferred program established and administered by the USDA. This program was created to reduce the use of, and reliance on, products made from fossil fuels while increasing the use of innovative products made from renewable agricultural crops and residues with an eye towards building markets, jobs, and economic opportunity for farm, forest and ocean-derived organic commodities. Producers are required to have their products tested by qualified, independent laboratories which submit results directly to the USDA for certification.

As a result of the current Farm Bill, the NRCS Environmental Quality Incentives Program (EQIP), broadened its purpose this year to include new or expected resource concerns for adapting to, and mitigating against, increasing weather volatility, and addressing drought resiliency measures. Improving soil health is a key component for farm resiliency to long term changes in weather such as increased temperatures and increased rainfall. Soil health is tied to soil organic matter and biochar is one method to increase this critical resource, as it provides ecosystem services such as increased water holding capacity, reduced erosion, and increased retention of nutrients. For fiscal year 2021, NRCS planners may have available (depending on the state) new practices such as: Soil Carbon Amendment (808); Soil Health Conservation Activity Plan (116); Agricultural Energy Design Plan (136); and Soil Testing Activity (216). The conservation practice related to biochar is the soil carbon amendment (NRCS 2020). These new methods that allow for biochar additions to soil are another step to develop the industry.

Increasing biochar production and use may come as part of other initiatives. For example, Draper (2019) pointed out that the Organics Materials Review Institute (OMRI) also certifies biochar under their 'ash' or 'wood ash' categories, both of which include crop fertilizer and soil amendments. Ash may be derived from either plant or animal sources. For wood ash, only untreated and unpainted wood is allowed. Ash from minerals and manures are specifically prohibited. The predominant focus for OMRI, beyond organic feedstock, is on safety of the soil amendment for human contact and application. They specifically test for three heavy metals: cadmium (Cd), lead (Pb), and arsenic (As). OMRI certification does not assess credibility (or legality) of any other claims on product labels.

Although not specific to the U.S., regulations in other countries may pave the way for greater biochar acceptance, production, and use. In Europe, biochar has been regulated as a soil amendment. The European Union (EU) has issued a brief on the topic of biochar regulation, noting that Switzerland was the first country in Europe to approve biochar for agricultural purposes. In Japan, biochar was approved for soil conditioning in 1984. In the EU, all chemical products must meet regulations set by the Registration, Evaluation, and Authorization of Chemicals. After meeting these regulations, the biochar needs a European Biochar Certificate to use it in agricultural production. In 2016, the European Biochar Certificate (EBC) issued guidelines for the sustainable production of biochar. The objective of these guidelines was to introduce a control mechanism based on the latest research and practices, taking into consideration regulations already in place in the EU.

The International Biochar Initiative (IBI 2015) encourages biochar industry development by providing standardized information about biochar characterization to assist in achieving more consistent levels of product quality. This standardized information was developed in collaboration with a wide variety of industry and academic experts and through public input at an international level and provides methods for biochar characterization for use as a soil amendment. The standards were also developed to assist biochar manufacturers in providing consumers with consistent access to credible information regarding qualitative and physicochemical properties of biochar and support the IBI Biochar Certification Program.

In the U.S. it is clear that continuing work is needed to develop, adopt, or improve the current biochar standards developed by the EU or the IBI. Also, work is needed with all the states, organizations, and federal agencies to define standards and establish national regulations such as those already included in the AAPFCO or USDA definitions.

CONCLUSION

Moderate-scale biochar production systems offer economic and ecological benefits that may not be realized using either small- or large-scale biochar production systems. Forest residues and small-diameter wood can be converted into biochar by using relocatable moderate-scale biochar production operations at and near the forest. This on-site biomass conversion provides a method to increase the value for biomass when biochar is sold at markets and decreases hauling costs as biochar moisture content is typically 15 - 25% (wet basis). A combination of these economic benefits (value increase and low hauling cost) can effectively improve economic feasibility of utilizing forest residues and small-diameter trees, resulting in less slash pile burning, and thus, improvement in soil and air quality.

However, the concept of producing biochar using relocatable biomass conversion technologies close to the supply of forest residues is in an early stage of development. Moderate scale biochar production technologies need improvements that increase daily production capacity, decrease production costs, and are easy to operate in the field. There is a further need to balance forest operations between biochar conversion and feedstock supply, which have not been extensively practiced on a regular basis. One key factor will be to educate logging operators to treat 'waste' feedstock as a commodity. The need to expand biochar markets is also identified as a key factor to enhance biochar business entrepreneurship. Furthermore, there are strong needs for increased utilization/applications of biochar, product standards and specifications, business innovations, and policy and regulatory support.

Our report includes three scenarios of moderate-scale biochar production industry development, illustrating technical and operational details that address barriers and apply strategies to improve business success. While specific strategies to enhance its economic feasibility may vary between operations, the following strategies would be able to substantively increase moderate-scale biochar production:

- Develop new and enhance existing moderate-scale biochar production technologies and perform techno-economic analysis to identify factors affecting economic viability.
- Expand biochar markets by conducting surveys to understand limitations and barriers, designing protocols and procedures that monetize carbon value, and enhancing customer awareness on economic and ecological benefits of biochar.
- Develop biochar products standards and specifications for safe use as a soil amendment, fertilizer, or water filter. Product testing is needed to understand biochar properties including pH, porosity, nutrients, and heavy metals from a variety of woody feedstocks.
- Expand and diversify businesses to reduce risks associated with unstable market price and demand for biochar products.
- Provide comprehensive business development resources to entrepreneurs and their partners to foster business, including policy and regulatory support.
- Offer technical assistance to producers and users of biochar to match biochar to end-use needs (i.e., soil and ecosystem functions).

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CHAPTER 6:

Centralized Biochar Production Facilities

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INTRODUCTION

In this chapter we describe the state of centralized production facilities and the challenges and opportunities for centralized biochar production. The authors considered strategies to develop centralized production, considering parameters such as markets, technology development, product development, environmental emissions, carbon efficiency, and education and training. Funding and investment opportunities were considered including developing an action plan, successful business models such as private public partnerships, strategic partnerships, and financial tools.

Centralized Facilities

Centralized facilities carbonize biomass to biochar at large scales and process it into value-added products. Centralized processing involves supplying biomass to the facilities and converting the biomass to biochar as a main product or as a co-product of electrical energy such as at a power plant, and/or heat energy such as might be used to cure lumber or dry grains (Miles 2021). Industrial-scale biomass operations (usually more than 100,000 tons per year [TPY] biomass feedstocks resulting in more than 30,000 TPY of biochar [300,000 cubic yards, CY]) require high capital investment to build large facilities, purchase several machines, and maintain a large operations crew. One-way hauling distances to these facilities are typically less than 100 miles.

There are examples of facilities of this scale in the U.S. and in the Pacific Northwest (PNW) region. The largest biochar plant in the U.S. (*National Carbon Technologies* in Minnesota) has the capacity to convert 150,000 tons of dry biomass to 50,000 tons of biochar, annually. The only charcoal plant in the PNW region (*Kingsford* in Springfield, Oregon) has capacity to convert 150,000 tons of wood residues to 50,000 tons charcoal for barbeque briquettes, annually. Now that some biochar markets have developed, the plant is making some biochar for soil application. The largest centralized biochar plant in the region, operated by the *Karr Group* in Onalaska, Washington, converts 20,000 TPY of mill residues to biochar.

Feedstock from Forests

Forest fuels removal to reduce the risk of wildfires could result in large quantities of biomass which could be converted to biochar. In many locations, the need for processing large quantities of biomass will be best met with centralized facilities. For example, California may have 9 million dry tons of agricultural residues and 14 million tons of forest residues available each year which could be converted to low carbon fuels while supplying substantial quantities of feedstock for biochar production (Williams et al. 2015; Breunig et al. 2019). Large-scale centralized facilities are needed to produce the quantities of biochar required to improve soil health, improve water quality, enhance compost, improve soils, and build green infrastructure in the region. Centralized facilities should have the economies of scale to make biochar at affordable prices for use on cropland and improvement of degraded land. A facility producing 50,000 TPY of biochar could supply enough biochar to treat 1,000,000 tons of compost at 5% (by weight) or treat 10,000 acres at 5 tons biochar per acre. If 50% of California's forest residues were converted to biochar, it would take 320 years until all of California's agricultural land would have received an application of biochar equivalent to 1% (w/w) in the top 6 inches of soil (Hunt & McIntosh 2019).

Feedstock from Other Woody and Agricultural Sources

Existing wood products industry, construction and demolition industries, biomass energy facilities, wood mills, and agricultural processing facilities provide an abundance of residues. The majority of mill residues in Oregon and Washington are used in engineered wood products. In Oregon, just 14% of mill residues are used for energy and only 0.01% of mill residues are not used (Oregon Department of Energy n.d.). Centralized facilities to process forest and mill residues could be co-located at existing energy plants, or at wood mill and agricultural processing facilities where they could share infrastructure, such as fuel transportation, storage, sizing, drying, and handling. Co-location at wood mills can take advantage of the availability of woody feedstocks, existing boilers that can be adapted to produce biochar, and established transportation infrastructure for wood and energy production processes. For more information, see *Chapter 9: Biomass Supply* and *Chapter 10: Biomass Handling*.

Biochar Recovery from Biomass Boilers

Some biomass boilers in the region recover biochar from the "fly ash" (small particles < 6 mm) captured from effluent gas streams or from "bottom ash" (particles that are too large to go up the stack and contain a higher carbon content than fly ash). Fly ash and bottom ash can be collected from boilers and, with some processing, can yield high quality biochar. Biomass boilers can be altered to produce more high carbon ash (Jensen & Moller 2018). When the carbon is harvested as biochar rather than burned as fuel, the outcome is either a correlated increase in feedstock throughput (to maintain the same energy output), or a correlated decrease in energy output. Since competing energy sources such as natural gas, wind, and solar have reduced the prices of energy below the breakeven point for biomass, converting biomass boilers to produce biochar could be attractive if biochar markets expand.

For example, *Biomass One* (Medford, Oregon; Figure 6.1) is a biomass power plant generating 32.5 megawatt electrical (MWe) (28.5 MWe goes to the grid). This plant consumes 200,000 TPY of dry biomass and can recover 50,000 cubic yards (CY) of biochar

Figure 6.1. *Biomass One in Medford, Oregon is an example of a centralized production facility. Production plant shown in background with hogfuel in foreground and supersacks of finished biochar. (Photo: Karl Strahl)*

annually. Process modifications allow Biomass One to recover biochar midstream, allowing a higher yield of biochar than if it were recovered through fly ash.

Opportunities exist to upgrade several plants to recover biochar. Biochar could be produced along with energy, or fuels in the case of torrefaction, a mild form of pyrolysis at temperatures typically between 200 and 320 °C. Boilers or torrefaction plants could add carbonizers and recover excess heat to dry fiber or generate steam. Wood pellet mills are centralized facilities that could make and use biochar to generate heat for their wood dryers. Concentrated agricultural residues like oat hulls also present opportunities for centralized production of biochar.

Compost as an Endpoint

Composting is an important strategy for management of urban green waste, food, and farm wastes. The composting industry is beginning to learn the benefits of adding biochar to improve the quality and reduce emissions from compost (see *Chapter 7: Biochar Produced and Utilized at Municipal Compost Facilities*, for further discussion of integrating biochar with compost). California, Washington, and Oregon rank among the top states in terms of organic waste diversion to composting, with amounts in these three states totaling 7.4 million tons per year (ILSR 2014; See *Chapter 9: Biomass Supply* for state agency data). A facility composting 80,000 tons of food and green waste can use 40,000 CY (4,000 dry tons) of biochar for inclusion in the composting process (Compost 2020).

Demand for biochar will increase as green infrastructure and environmental remediation grow in the region. Remediation of abandoned mines is another potential demand for large quantities of biochar. The Walker Mine in California could consume 2,500 CY (300 tons) of biochar (Larry Swan, USFS Region 5, personal communication).

A large, centralized facility could provide enough capacity to offer multiple benefits including:

- Reduction of fire hazards arising from overcrowded forests;
- Associated major benefits in fine particle (PM2.5) reductions and health impacts due to wildfire reduction;
- Reduction/elimination of open burning in agriculture;
- Increase in rural area employment and investment;
- Expansion of baseload renewable electric power;
- Retention within the region of monies spent on carbon credits (generating local employment and economic benefits) rather than sending those funds abroad for renewable fuels from imported feedstocks;
- Reduction in costs of carbon credits due to expanded supply in both Low Carbon Fuel Standards and cap and trade, lowering costs for all consumers across the economy; and
- Reduction of water use and drought-associated crop risk.

The following sections will explore these benefits and describe: 1) challenges for centralized processing facilities, 2) strategies to develop centralized biochar processing, and 3) opportunities for investment in research and infrastructure. Strategies include market development, with a focus on carbon markets, technology development, education, and training. Funding and investment opportunities include developing an action plan, initiating successful business models such as cooperative arrangements, public/private partnerships, and strategic partnerships, and developing decision making tools and financial instruments.

CHALLENGES FOR CENTRALIZED PROCESSING

Scaling up biochar production in centralized facilities is challenged by limited markets, high transport cost of feedstocks, the small scale of the existing industry, and large capital requirements.

Current Markets and Market Impediments for Biochar

Some current markets for biochar are soil amendments for gardens and landscaping where volumes are low and prices are high, so biochars are often more expensive than farmers can afford. Demand can be unstable as markets grow, so a large plant must absorb swings in demand and value of finished product. The production capacity of centralized biochar facilities may be greater than current biochar demand. A large Midwest producer (*National Carbon Technologies*) supplies charcoal produced without fossil fuel energy to the metals industry as a way to subsidize their biochar production. While the benefits of biochar can be demonstrated, developers of centralized facilities are challenged to convince investors that markets are sufficient to support investment in new, larger facilities. Current markets and monetized benefits (e.g., carbon credits, subsidies) are not large enough to generate sufficient cash flow to finance centralized facilities. For carbon markets to evolve, investors require a biochar carbon accounting protocol and guaranteed offtake agreements. Public subsidies have been suggested to stimulate market demand and to enable new plants to supply products during the gaps in demand that occur during new product acceptance. Market development through policy often takes a long time. Biochar has not taken advantage of current carbon markets and policies, such as cap and trade and Low Carbon Fuel Standards (LCFS), even though waste grains, fats, and oils are being imported to supply this market.

Scale, Capital Cost, and Feedstock Transport

The biochar industry is currently small. There are 45 suppliers in the region: 25 in California, 11 in Oregon, and nine in Washington. The industry is stratified with a few large producers and many small producers, many of which broker for larger producers. Much of the biochar is produced as a byproduct at only a few of the existing bioenergy plants in Washington, Oregon, and California. Some biochar is imported into the region from Colorado (U.S. Biochar Initiative, unpublished). Small producers have limited access to capital and must rely on market guarantees to finance investments and on sales to fund operations. With limited sales volumes, producers must cross the so called "valley of death" (the period of time between startup and profitability) in which there is limited access to capital. Centralized facilities are large investments that require demonstration of guaranteed benefits. Capital requirements are large for centralized facilities due to equipment size, the industrial nature of production, and the pollution control equipment required in an industrial plant. Investors may also be concerned about long term supplies of feedstocks for centralized facilities but estimates of biomass availability are large as detailed in *Chapter 9: Biomass Supply*.

Despite the abundance of potential feedstocks, the delivered cost of feedstocks like forest residues can be high relative to their value. Possible solutions to this issue, including the conversion of forest residues into a variety of products in a Biomass Utilization Campus, are discussed later in this chapter.

STRATEGIES FOR CENTRALIZED PROCESSING

Here we discuss strategies for developing centralized processing facilities. These strategies include: 1) increasing supply of low-cost feedstock, 2) developing appropriate production technologies, 3) further developing products, 4) expanding education and training, and 5) tapping into carbon markets.

Increasing Supply of Low-Cost Feedstock

Biochar feedstocks are abundant and market development by existing suppliers has shown promise in disposal and reuse of urban wood and oversized wood ("overs") from composting. CalRecyle estimates that 3.8 million tons of urban wood are available in addition to 1.3 million tons currently used for bioenergy (CalRecyle n.d.). The urban wood could be converted to more than a million tons of biochar. Since urban wood is delivered with a tipping fee, the biochar could potentially be delivered at a lower cost to agricultural consumers. Compost producers often pay high tipping fees to dispose of oversize wood ("overs") from composting. Much of this material is landfilled. Large quantities of compost overs are available from green waste and food waste compost facilities in the region that could supply centralized biochar facilities.

Another potential feedstock for centralized biochar facilities is forest residues from wildfire fuel reduction efforts. California, Washington, and Oregon are among the top ten states with significant risk of wildfire. An estimated 2 million homes in California are threatened by wildfire (Insurance Information Institute n.d.). These states already have some of the infrastructure to harvest forest fuels and deliver them to centralized bioenergy facilities. Biochar production and utilization offers a pathway to offset some of the cost of forest fuels reduction that currently burdens federal, state, and private entities. Centralized facilities can offer partnerships for large-scale forest biomass management.

Current estimates show that forest biomass in California could generate 1.5 million tons of biochar annually which could amend 160,000 acres of land at an application rate of 9 tons per acre, roughly equivalent to 1% soil organic matter in the top 6 inches of soil. That annual application would add 13,000 acre-feet of water holding capacity and could achieve a carbon drawdown of 3.75 million tons of carbon dioxide equivalent (CO_2e) at a cost of $35 per ton when considering carbon dioxide reduction and emission reduction combined (Hunt & McIntosh 2019). A subsidy for forest restoration or fire hazard reduction could be provided to ensure a long-term market, similar to the "Standard Offer No.4" contracts in California that guaranteed a fixed power price for a period of ten years (California Code).

Production Technology Development

The production of biochar at large scale can in principle be accomplished in combination with other products (heat, syngas, liquid fuel) or by targeting the production of biochar alone. This can be achieved with many types of designs, each of which consider varying feeding types, heating mechanisms, construction materials, and reactor positions (see *Chapter 11: Biochar Production*.) From an economic standpoint, heat and biochar production are most efficiently achieved today with modified Stoker boilers. The production of biochar and gases is typically achieved with the use of gasifiers at temperatures over 800 °C. High yields of liquids (over 70% by weight) and biochar are accomplished with so-called fast pyrolysis reactors. In practice, most fast pyrolysis reactors use the biochar produced as a source of internal heat. Slow pyrolysis is by far today the most commonly used technology for biochar production and the most efficient in terms of the fraction of biomass carbon converted to biochar. However, at small scale facilities, the liquid produced can be released to the atmosphere in the form of highly visible aerosols and vapors (i.e., smoke), harming the environment and contributing to the negative public perception of this technology.

The yield of biochar can be maximized by new carbonization technologies (e.g., using high pressure or strong acids; T.R. Miles, personal communication). There are ongoing efforts in the U.S. and Canada to scale up these technologies. Further modifications to Stoker grate boilers also have the potential to increase the fraction of biochar produced for a given level of bioenergy output (K. Strahl, Biomass One, personal communication). Our assessment is that in the years to come we will see an increase in biochar and power production in modified Stoker boilers and also major developments in dedicated technologies maximizing biochar production (slow pyrolysis with pollution control or new carbonization methods). Centralized facilities provide opportunities for co-processing, co-generation, and large-scale production of value-added biochar products.

Product Development

The availability of large volumes of a low-cost and sustainable carbon feedstock could catalyze the creation of a "Green Carbon Economy." Centralized biochar production at new or existing facilities could be a major source of low-cost carbon for the development of value-added products.

Expansion of markets will involve companies specialized in carbon products for two separate types of markets: 1) low-cost/high-volume and 2) high-cost/low-volume markets.

Examples of low-cost/high-volume markets are agricultural soil amendments; horticultural applications where biochar can be used as a substitute for peat moss, perlite, or vermiculite; animal feed; construction materials; and environmental services, such as stormwater filtration or wastewater treatment (Boehm et al. 2020; Imhoff & Nakhli 2017; Miles et al. 2016; MPCA n.d.; Ulrich et al. 2015). Biochar suppliers estimate that expanding existing markets could create sufficient demand to support centralized facilities (T.R. Miles, personal communication). The standards and specifications needed to expand markets for these applications are still in development in Washington, California, Delaware, and Minnesota (T.R. Miles, personal communication).

Examples of high-cost/low-volume markets include applications for highly functionalized carbons such as carbon nanotubes, carbon gels, and carbon fibers that can be used as catalysts, and in fuel cells, batteries, and electrodes. For centuries carbon has also been used as the preferred reducing agent in some metallurgic technologies.

Some of the modifications widely used today to enhance carbon performance include increasing surface area through physical activation (with carbon dioxide [CO_2] or steam), oxidation with strong acids or oxidants (oxygen [O_2], ozone [O_3], hydrogen peroxide [H_2O_2]) to form surface carboxyl and carbonyl functional groups, and nitrogen-doping (reaction with ammonia [NH_3] or co-processing with nitrogen sources). Other functionalization strategies such as co-composting and the addition of metals and enzymes have also been explored. Because of the vast number of potential applications and products, it would be highly advantageous to catalyze the creation of carbon companies specializing in targeted products and markets.

Education and Training

In order to deploy improvements in production technology to expand products, it will be necessary to train a large number of specialists with skills that will enable them to work in this industry. We need to develop teaching tools for high school students, undergraduate students, graduate students, and practitioners. It will be very important to take advantage of on-line tools to prepare courses with hands-on tasks to reach thousands of students around the world in the production and use of carbon products. Associations with groups such as Chemists Without Borders, the United States Biochar Initiative (USBI), and the International Biochar Initiative (IBI) could be very helpful in this effort.

Carbon Markets

The widespread development of carbon markets for biochar would strengthen the case for large, centralized facilities to meet the increased demand. At the time of this report, Carbon Future estimated that the net average value of biochar is about 2.5 tons CO_2e per ton of biochar (Carbon Future n.d.). Thus, a facility producing 50,000 TPY of biochar would sequester carbon equal to 125,000 tons of CO_2e (50,000 tons × 2.5 tons CO_2e), which at a (hopeful) future price of $70 per ton CO_2e could generate revenues of $8.8 million per year. That is equal to $175 per ton of biochar or $44 per ton of forest residues delivered to the plant (assuming 4 tons feedstock per ton biochar). If the 50,000 tons of biochar were sold at $500 per ton ($50 per CY, $0.25 per lb), this would generate $25 million per year in gross revenue. If energy was recovered from the plant, it could be sold as heat for an additional $1 million (107,000 MMBtu × $10 per MMBtu) or power for an additional $2.7 million (6 MWe × 0.85 × 8,760 h × $60 per MW-h). Co-location strategies with existing industries should be pursued whenever possible to reduce capital costs. Co-generation opportunities are critical for heat commercialization.

Centralized facilities can take advantage of the large carbon market demand if products comply with existing standards. In order to access carbon markets, standard biochar characterization methods and protocols must be adopted for multiple uses. Protocols exist and can be used: *Carbon Future*, an emerging carbon market platform, requires either a European Biochar Certificate (EBC) or International Biochar Initiative (IBI) certificate for verification. *Puro Earth*, from Finland, is another voluntary carbon market which will only accept biochar that meets the EBC standard.

DEVELOPING AN ACTION PLAN FOR CENTRALIZED BIOCHAR FACILITIES: OPPORTUNITIES, BARRIERS AND RISKS

Modification of Existing Biomass Plants

Biochar production at centralized facilities can be achieved in many ways. One pathway is to modify existing biomass power plants. This method is considered "low hanging fruit," as it is relatively quick, low cost, and can result in large-scale production of high-quality biochar.

Modification "Lite"

Several biomass power plants in the region burn wood in a furnace combined with a boiler to make steam for electricity generation or heat to dry lumber. They are like giant wood ovens with a continuous supply of wood chips and fresh air burning on a grate. The air flow is strong enough that it pulls out most everything but the rocks and sand that fall through the grate. Caught in the draft is a mixture of biochar and mineral ash. Biochar particles are mechanically removed from the mineral ash for the purpose of being re-burned for their energy value. By modifying the equipment and operating procedures of such a facility, biochar can be separated from the ash and harvested for use as biochar instead of being burned for fuel. The equipment to separate the biochar, including air locks, augers, chain drags, and other biomass handling equipment, are readily available. The methods used are novel but have already proven successful at several facilities. The biochar then needs to be properly stored and wetted before transportation. In this case about 2% of the dry fuel fed to the boiler can be recovered as biochar. This modification can be achieved in approximately 2 to 6 months. A 20 MW biomass plant can potentially recover about 5,000 tons (50,000 CY) of biochar per year.

Modification "Super-Lite"

Sometimes, in certain boilers, when the biochar is not screened from the fine mineral ash but rather is allowed to be dumped out as one "unfiltered" product, it can result in a material with charcoal content that is so high that the "ash" is mostly charcoal (biochar). There are modifications in equipment and changes in operating parameters that can make this approach successful even at facilities where it is not otherwise feasible. The resulting biochar will have a relatively high mineral ash content, which can be beneficial in certain applications. This modification can be achieved in a similar time frame as modification "lite" and recover a comparable quantity of biochar.

Modification "Heavy": Adding A Carbonizer

A separate dryer and carbonizer can be added alongside an existing boiler that is using the technologies previously described. A slow pyrolysis system can be carefully controlled so the quality of the biochar could be tuned to particular market needs. It would recover about 30% of the fuel (45% of the carbon) fed to it as biochar. The dryer and carbonizer would share the fuel delivery, storage, and handling systems with the boiler. A third of the energy in the fuel would be available as fuel gas which could be routed to and burned in the existing boiler. There would be a cost in retrofitting an appropriate burner to the existing boiler, but there would be no change in the pollution control equipment in the boiler, or to the electricity generation equipment associated. The fuel dryer would require emissions control. The plant could produce the same amount of power while consuming additional fuel to convert to biochar. One boiler in the U.S. has been retrofitted with a carbonizer. Carbonizers for this application typically each consume 2 to 6 dry tons of fuel per hour and could produce up to 15,000 tons (150,000 CY) of biochar per year per carbonizer installed. The number of carbonizers installed would depend on the design of the boiler and the biomass plant facility. Addition of this biochar process line, including design, permitting, construction and commissioning, could take from one to three years depending on the location and capacity.

Modification costs vary depending on the existing plant design, the available space, and the topography upon which the facility is built. Modification "super-lite" has been accomplished at one facility with zero additional infrastructure cost. Modification "lite" has been accomplished for as little as $100,000 in machinery and labor, but it could cost between $250,000 and $1,000,000 at most suitable biomass power facilities that are in the range of 10 to 30 MW. Adding a dryer and carbonizer can cost from $3 to $6 million per process line depending on the existing infrastructure and the chosen pyrolysis technology.

Development of Environmental and Economic Studies

The environmental application of wood ash to soils should be reviewed, as it can provide insight into other ways of easily incorporating biochar into various uses. Several million tons of high carbon wood ash generated at biomass power plants have been land-applied in the western region, spanning at least three decades, covering more than a hundred thousand acres. While high carbon wood ash is not the same as what we would normally consider biochar, it includes biochar as a component: high carbon wood ash commonly has a carbon content between 25% and 45%. Ten million tons of high carbon wood ash with an average carbon content of 35%, therefore, is equivalent to 4.1 million tons of a biochar with 85% carbon content. It can be thought of as biochar floating in ash. And though the responses observed immediately after application may be predominantly a result of the mineral and pH influences of the ash, the charcoal fraction is recalcitrant, and its effect can be observed for decades. This becomes clearer as the influence of the ash diminishes; soils with historic wood ash applications are visibly darker (J. Hunt, personal communication).

Environmental studies should be developed to re-examine and re-emphasize the benefits of land applying wood ash. Historically, wood ash from biomass boilers in the U.S. was land applied, however a large portion of wood ash is now landfilled due to changes in regulations that make the boiler owner responsible for adverse impacts of the ash, difficulties with contractors removing ash, and other factors which appear to boiler owners as liabilities (T.R. Miles, personal communication; Risse & Gaskin 2013). Research into the environmental benefits of wood ash application to soil would work to reverse this trend and turn an ostensible liability back into a resource.

The PNW region has both existing infrastructure and an abundance of available agricultural residues and forest fuels. The economic feasibility of converting existing boilers to produce biochar warrants further investigation to determine circumstances and incentives needed to optimize biochar production. In addition to the cost of retrofits, the cost to produce biochar in these facilities is determined by 1) the value of the electrical energy not generated when the recovered biochar is harvested rather than burned as fuel, or 2) the cost of the additional feedstock required to maintain energy output when biochar is harvested rather than burned. These two different scenarios result in different economic outcomes, effectively determining the cost of biochar production as either energy not sold, or extra fuel purchased. Depending on the value of energy and the cost of feedstock, individual facilities can decide how to optimize their operation to maximize revenue. This can and does change seasonally. It could be useful to the industry if a technoeconomic analysis were developed to model biochar production costs in a variety of situations as mentioned above.

Development of Successful Business Models

The difficulty with any endeavor that involves a promising new and substantial market is to persuade knowledgeable investors to take on the initial expense. These investors must be fully aware of the risk involved in the undertaking. For any business model proposing a first-off facility, the capital investment risk is typically large and usually offset by contractual assurances that the facility's product has a guaranteed buyer. From the perspective of the buyer, the risk can be every bit as substantial, especially if there are alternatives to the product or business as usual continues to be viable. Risk is reduced if there are assurances that the production facility has capital financing and competent staff to build and operate the facility. This "chicken and egg" conflict is the conundrum faced by those producing charred woody products such as biochar and torrefied biomass (discussed below). Biochar has market potential as a proven soil amendment that can promote nutrient and water retention in the soil column for agricultural and forest lands while torrefied biomass is now a proven, renewable fuel substitute for fossil coal at power generation stations. Both applications have carbon-neutral to potentially carbon-negative impacts. New markets are evolving for biochar as a method of carbon removal. The impact on production is not clear since prices in the smaller voluntary markets are high compared with the larger regulated markets.

Successful business models for full-scale manufacture of these products should be developed for centralized facilities. Here we describe two possible examples: a Biomass Utilization Campus and a torrefaction/biochar facility. Options considered include collective ownership models, integrated processing, public-private partnerships, as well as aids and subsidies such as strategic partnerships, policy, and financial instruments, discussed in the next section.

Biomass Utilization Campus

A Biomass Utilization Campus (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. Integrated processing in a BUC may allow for the avoidance of a Brush Disposal Deposit within U.S. Forest service timber sales, which could reduce timber sale bid prices. It could potentially have a cumulative benefit to states where timber sales fund infrastructure, schools, and other public services. There are examples of integrated biomass utilization based on stewardship contracts in Oregon. One facility in Wallowa, Oregon, which makes firewood, posts, and poles, will begin to produce biochar as a co-product of heat they generate for their firewood kilns. Demand for the biochar enhanced soil amendment is from their marketing and distribution partners in Washington, Oregon, and California. This model could be expanded with the integration of companies engineering carbon products at centralized facilities.

Public/Private Partnership: Torrefaction/Biochar Facility

The majority of biochar producers in the PNW operate on very small scales and usually as a by-product of a gasification or combustion facility where the produced gases are typically consumed as a fuel to produce electricity. There have been attempts at creating production facilities for torrefied biomass at the rate of 2 to 5 tons per hour but most of these attempts have failed due inadequate funding, lack of contractual offtake, and/or construction delays. One commercial scale facility at 12 tons per hour output is expected to be operational by late 2021 in John Day, Oregon. Upon completion and commissioning, this torrefaction facility will be the only commercial scale torrefaction plant on the planet (*Restoration Fuels*; Figure 6.2). Capital funding for this facility has been provided primarily by the U.S. Endowment for Forestry and Communities (Endowment), a non-profit that is driven by its mission to improve forest health and promote economic development in the forest/wood products sector. The investment aim is to source the torrefied wood feedstock from overgrown, diseased, and dry inland western forests. Removal of this small diameter, low- to no-value material

Figure 6.2. *Torrefaction system at Restoration Fuels in John Day, Oregon. (Photo: Matt Krumenauer)*

reduces the excess fuel loading that has resulted from nearly a century of forest fire prevention policy. Torrefaction of the green wood is required to increase the energy value and, most importantly, to make the fuel sufficiently friable for crushing in pulverized coal power plants that dominate solid fuel-fired, electrical generating stations worldwide.

The Endowment, with support from the U.S. Forest Service, has accepted the investment risk necessary to develop a market where the demand can be so high that it stimulates a "market pull," initiating a virtuous cycle that further improves forest health and creates jobs to support that market. Coal-fired power plants that substitute renewable torrefied fuel use millions of tons of fuel annually and comprise a substantial market even if the increased cost of torrefied fuel relegates its use to seasonal applications where power costs ramp up from high demand due to air conditioning in the summer and heating in the winter. The same type of market demand can be envisioned for biochar.

The production processes for biochar and torrefied biomass are remarkably similar. Typically, they involve source gathering for the material infeed, chipping, drying, thermal application in a kiln at atmospheric pressure, cooling, and then, depending on transportation distances, densification to a usable form factor (e.g., a pellet or briquette). Densification supports dust control for operational safety, increases bulk density for cost-effective transportation, and when consumed at a power plant, helps to mimic the energy density of coal in the power plant's fuel conveyance system. The main difference between biochar production and torrefied wood production is temperature: torrefaction occurs between 250 and 300 °C while biochar production requires a temperature greater than 450 °C. That said, it is quite possible that a kiln-type torrefaction facility could accommodate a parallel system to produce biochar. This assumes that sufficient footprint and infrastructure are available at the torrefaction facility location.

This "shared-footprint" concept bolsters the evolution of an additional product that supports an entirely different market segment while sharing the capital costs across both processes. As the feedstock material will likely be the same, the original efficacy and rationale of the torrefaction facility increases. Although operational costs and labor will likely increase for the combined facility, given the shared nature of the concept, it is likely that efficiencies will be realized. In contrast, separate facilities where the capital and operational costs might mirror themselves in the worst case may be twice as high as a shared facility.

Moreover, such a shared facility, which is a variant of the Biomass Utilization Campus idea, not only reduces capital investment risk but would also merge societal concerns and industrial segments. Torrefied, biogenic wood fuel displacing fossil coal provides renewable power, involving both forestry and power generation industries. Biochar production and use improves soil health and productivity for forestry and agricultural industries. In both applications, near carbon neutrality is achieved that, when realized at scale, can make a notable contribution to climate change mitigation.

Strategic Partnerships

Regulated electric utilities are granted monopolistic service territories with pricing and service quality monitored closely by a governmental utility agency. In exchange for the monopoly, the utility is granted a guaranteed rate of return on infrastructure investment and has the "obligation to serve" all customers in their allotted territory. Over time this model has changed to one in which larger customers and power users, such as many high tech and consumer brands, have been granted the ability to negotiate their exit from the regulated structure. Public statements and efforts to remove themselves from the regulated market have originated from companies such as Microsoft, Amazon, Mars Inc., Weyerhaeuser, Georgia Pacific, ADM, Cargill, and Walmart, to name a few. Typically, these companies are looking for improved electricity pricing and, more significantly, for electricity from renewable power sources. The latter applies to many companies looking to address their customers' or stakeholders' concerns specifically over impacts of climate change and more generally to make their operations and products more environmentally sustainable.

This movement has opened opportunities for independent power producers to address the market and provide renewable power to very specific end customers. Although the bulk of the renewable power market focuses on wind and solar power, biomass is also part of this mix and thus, can make inroads to this market demand. Even though in most states in the U.S., biomass, whether pyrolyzed to gas and biochar or used directly as a solid fuel, qualifies as a renewable source of power, broad societal support is needed to advance sustainable use of biomass as a renewable power source. Typically, this means obtaining the concurrence and support from environmental non-governmental organizations (NGOs) for the combustion processes related to the use of non-fossil biomass fuel. It is likely that featuring biochar application as a means to improve soil health could positively influence this support. It would certainly be an attractive and strategic outcome. For example, an NGO such as the Blue Mountain Forest Partnership could team up with Microsoft or Apple for this type of promotion that advances the use of biomass-based, renewable power with co-benefits in healthier forests and sustainable agriculture.

Financial Instruments

Working capital, or the lack of it, can be a determining factor in the growth rate and success of a company, and is particularly important in a nascent industry that can occasionally experience rapid growth cycles. The ability to turn accounts receivable into working capital can help ensure a company is able to meet client demands. If there were to exist a financial group that offered such services specifically catered to the biochar industry, such a financial tool would be very useful for building centralized biochar facilities.

Biochar Sales on Net 5 Year for Agricultural Applications

Biochar can pay for itself if given sufficient time. Generally, where biochar can realize greatest value is in agriculture applications where soil is poor and/or where crop value per acre is high. For instance, were biochar to be applied in a field of wheat (generally low crop value per acre) where the soil is already fertile, the payback may take decades. However, were biochar to be applied to a vineyard (generally high crop value per acre) where soil is poor, the payback may be realized in a single harvest.

At least a portion of farms or crops can be identified as having a high likelihood of yielding a positive return on investment for biochar applications within a five-year period. This could decrease the risk to lenders and, assuming the biochar in question is verified as sustainably produced, there would also exist long lasting benefits to the local environment and governing entities. This appears to be fertile ground for a state-backed or philanthropically minded loan program to help play a role in biochar deployment.

Carbon Credit Advances

In a situation where biochar carbon credits were issued for verified biochar applications and where a biochar production and application event has been planned and confirmed but not yet deployed, the advance distribution of the carbon credit could be very useful in solving some of the working capital constraints that might otherwise exist. This carbon credit advance could be issued directly by the carbon trading entity, or potentially by a fee-based third party.

Other tools that could support biochar industry growth, but not discussed in more detail here, are purchase order financing, invoice financing, and factoring catered to growing the biochar industry.

CONCLUSIONS AND KEY RECOMMENDATIONS

The PNW region presents opportunities to produce biochar and co-products in centralized facilities. The region needs forest fuel reduction in watershed uplands and soil improvement and carbon sequestration with biochar in watershed lowlands. Simply, when we stand back and gain a broad perspective, some watersheds in the dry western U.S. will benefit from a redistribution of organic matter. This redistribution can be achieved with biochar production. Biomass resources are abundant. Existing infrastructure exists to supply centralized facilities. Centralized processing provides many benefits we have considered. Challenges to centralized processing include pricing and market issues associated with an embryonic industry, delivered costs of feedstocks, and capital financing.

Our key recommendations for expanding production of biochar in centralized facilities are as follows:

- Develop and scale market opportunities.
- Develop appropriate technologies that take advantage of centralized processing.
- Develop products for enhanced carbon applications.
- Educate and train an army of carbon specialists.
- Modify existing biomass plants to recover carbon and co-produce biochar.
- Develop economic and environmental studies that show the benefits of centralized processing such as the expanded application of high carbon wood ash, conversion of existing facilities, and optimization of carbon markets.
- Develop successful business models such as biomass utilization campuses and public private partnerships.
- Develop financial instrument such as purchase order financing, invoice financing and factoring or biochar sales arrangements based on five year soil improvements.
- Exploit carbon markets such as cap and trade and Low Carbon Fuel Standards (LCFS).
- Advance carbon credits to finance the use of biochar in agricultural applications up front thereby facilitating adoption.

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CHAPTER 7:

Biochar Produced and Utilized at Municipal Compost Facilities

Mark R. Fuchs, B. Thomas Jobson, Douglas P. Collins, Edward Wheeler, and Bruce Springsteen

OVERVIEW

Background and Motivation

Composting, the biological breakdown of biomass to more stable organic matter, is a broadly applied method to reduce landfill disposal of the organic fraction of municipal solid waste and to create a useable and sustainable process for recycling organics. The diversion of organic waste generated in urban areas from landfills to compost facilities has multiple benefits including preserving landfill capacity, reducing greenhouse gas (GHG) emissions (in particular, methane; Jobson & Khosravi 2019), as well as providing environmental benefits associated with application of finished municipal solid waste compost to agricultural lands (Martinez-Blanco et al. 2013).

Composting facilities process a significant amount of woody biomass that makes its way into the solid waste collection system. This woody biomass is suitable for biochar production and, thus, presents an opportunity for integrating these two organic waste treatment strategies—composting and biochar production—to advance the biochar industry in the Pacific Northwest. Facilities could capitalize on efficiencies of co-location and existing markets for soil amendments, while providing benefits to the composting process in terms of odorous and GHG emission reduction. In addition, there are indications that adding biochar to traditional feedstocks at the beginning of the composting process, also called "co-composting" can yield a soil amendment that is superior to biochar or compost alone.

In this chapter, we describe the potential that compost facilities represent for biochar production in terms of wood recovery. Next, we discuss the potential benefits of co-composting with biochar. Third, we address some of the characteristics of compost facilities that are important to consider in siting co-located biochar production. Finally, we discuss barriers to co-location of biochar production with compost facilities and make recommendations for overcoming these barriers.

Wood Recovered and Recycled in Compost

Composting of organic wastes has been underway for over 30 years in Washington, Oregon, and California. As an example of these systems, we will describe the situation in Washington. Figure 7.1 shows a map of the 60 compost facilities listed in the Washington Department of Ecology annual report database for 2018. Two dozen of these locations primarily compost municipal organic feedstocks, including yard debris, land clearing debris, food waste, sawdust and shavings, other wood debris, and mixed food-yard debris. Figure 7.2 shows the composition of feedstocks (sum of all facilities) from 2010 to 2017, though there is substantial variation between facilities.

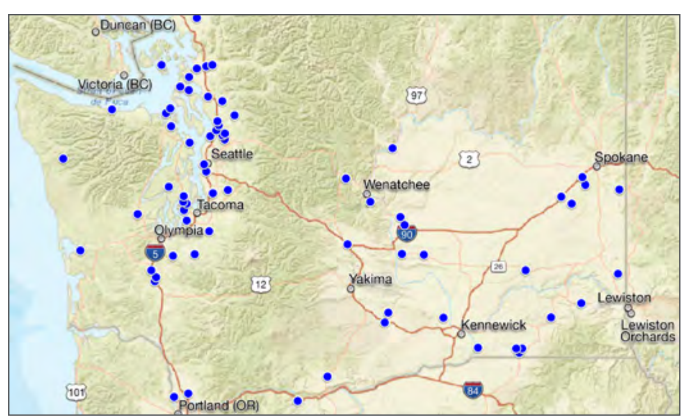

Figure 7.1. *Compost Facilities in Washington State (Source: Ecology n.d.).*

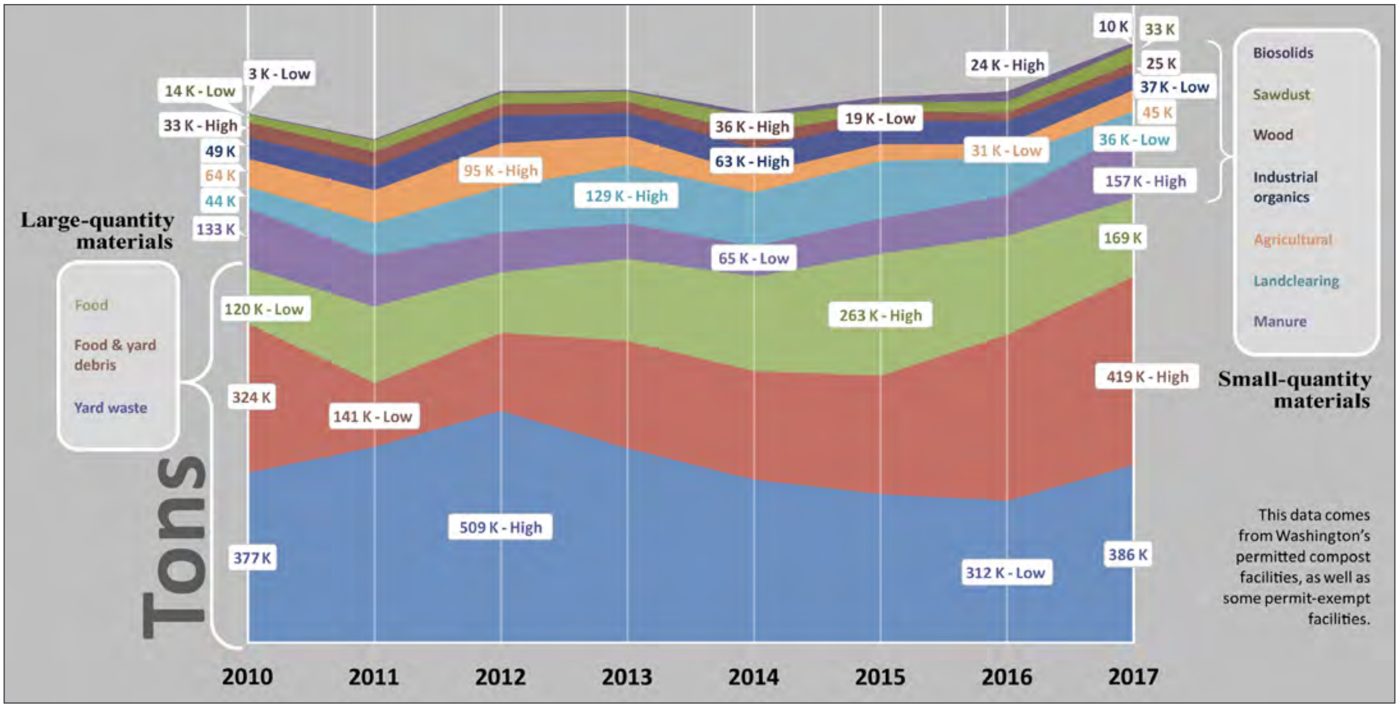

Figure 7.2. *Materials composted in Washington annually 2010 to 2017. (Source: Ecology n.d.)*

Washington, because of its urban and agricultural centers, generates a variety of feedstocks, including pre- and post-consumer food wastes, agricultural residuals, wood waste, biosolids, and other organic and woody materials. Wood waste, however, represents a small portion of the component of the total composted materials in Washington (Figure 7.2). In 2017, Washington compost facility annual reports show that wood biomass including land clearing and wood debris represent about 5% of the feedstock composted at all locations. Up to roughly 10-15% of yard debris and yard waste is wood waste, as confirmed with several compost operators (Scott Deatherage & Edward Wheeler, personal communication). Estimates of urban wood waste in the region are presented in *Chapter 9: Biomass Supply*.

Many composters mechanically reduce the size of limbs and woody biomass to a diameter of four inches or smaller. The woody biomass is further shortened and provides a bulking agent in the compost operation that promotes the movement of atmospheric oxygen into and through the piles. These large wood pieces do not disintegrate quickly and, when composting is complete, are screened out from the finished product. These "overs" along with other large uncomposted debris are re-used as bulking agents to improve porosity in new compost piles. Compost overs are a potential source of biomass for biochar production on the facility premises. A schematic showing potential integration of biochar into a compost facility is shown in Figure 7.3.

CO-COMPOSTING WITH BIOCHAR

The following section explores in more detail the benefits of why a compost facility might want to co-compost with biochar; subsequent sections outline factors that compost facilities both have to consider generally and those more specific elements that should be evaluated when considering co-locating biochar and compost facilities.

Growth and Yield Benefits

Recent literature suggests that there are agricultural benefits to the application of biochar that has been composted with other traditional compost feedstocks (Gang 2018). While co-composted biochar generally benefits plant growth and yields, results range widely and likely depend on the combination of biochar properties, soil, and crop type.

Plant growth trials on regionally relevant specialty crops have shown promise. For example, studies at Washington State University (WSU) with sweet basil grown in greenhouse pots show that basil grown in field soil blended with co-composted biochar (2.5% and 5% biochar by volume) enhanced growth rates and yields. No impact on growth rates was observed when pure biochar or pure compost were mixed together at the same ratios (Gang et al. 2018).

Since the Gang et al. report, a growing number of studies, many of which are relevant to agriculture and the composting industry, have shown the potential agronomic benefits of co-composting with biochar (Godlewska et al. 2017; Agegnehu et al. 2017; Sanchez-Monedero et al. 2018; Akdeniz 2019; Wang et al. 2019). At rates of 5% to 10% addition of biochar by volume at the beginning of the compost process, significant benefits were observed. Most of the studies were co-composting with animal manures, principally chicken, pig, and cattle, and involved small scale lab trials rather than full scale composting. There are far fewer studies where biochar has been added to the organic fraction of municipal solid waste (Malinowski et al. 2019), something that deserves more study. Co-composted biochar appears to be a better soil amendment than compost or biochar alone (Schultz et al. 2013; Agegnehu et al. 2017; Wang et al. 2019) as demonstrated through evaluation on crop plant growth and the aforementioned yields in potted plant experiments and field trials. Adding biochar may thus enhance the commercial value of composts produced in urban markets—but more studies are needed on biochar co-composting with the organic fraction of municipal solid waste. In addition, more definitive trials with co-composting biochar with animal manures are also needed.

Nutrient Capture

One explanation for the exceptional soil amendment properties of co-composted biochar is the ability of biochar to capture nutrients (nitrogen, phosphorus, potassium) from the composting process, allowing for their long term release into the soil (Kammann et al. 2015). Microscale surface chemical analysis of the co-composted biochar shows that nutrients are captured both in the biochar pore space and as an organo-mineral "plaque" formed on exterior surfaces (Hagemann et al. 2017). Biochar thus appears to be chemically modified by the composting process.

The addition of biochar to composting material has been noted as one of the most effective methods for reducing nitrogen loss (Sanchez-Monedero et al. 2019). A number of studies with manure composts have demonstrated that co-composting with biochar increased total available nitrogen in the resulting material (Chen et al. 2010; Prost et al. 2013; Khan et al. 2014; Kammann et al. 2015; Lopez-Cano et al. 2016).

The capture of nutrients also has important environmental benefits. For example, the capture of nitrogen could mitigate environmental losses such as:

- Nitrate (NO_3^-) into surface and ground waters which contributes to eutrophication of waterways

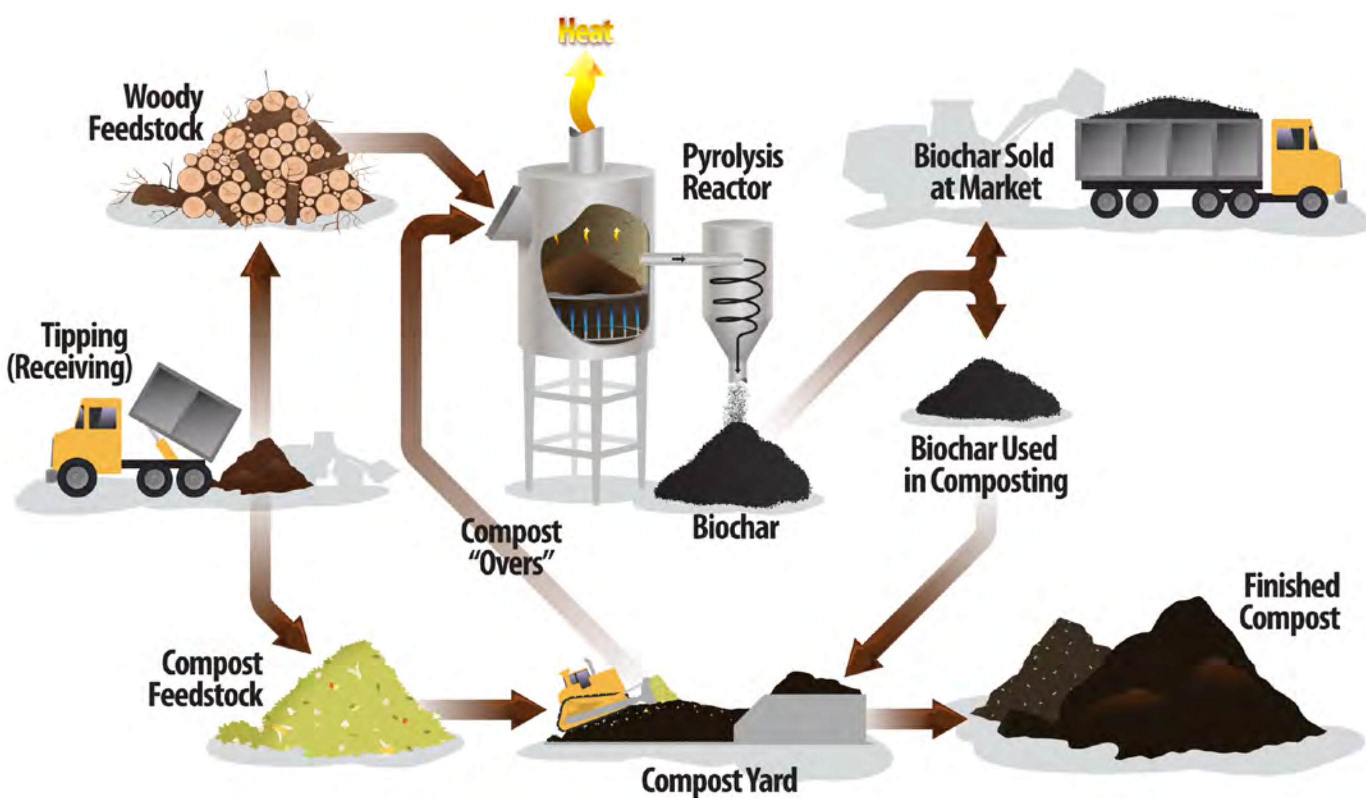

Figure 7.3. *A schematic showing concept for integration of biochar production into a compost facility. (Credit: Andrew Mack, Washington State University)*

- Gaseous emissions of ammonia (NH_3) which can cause odor problems and contribute to particulate matter pollution ($PM_{2.5}$) through formation of aerosol ammonium nitrate (Paulot & Jacob 2014).
- Nitrous oxide (N_2O) emissions which is both a potent GHG (GWP_{100} = 293) and a major contributor to stratospheric ozone loss through production of NOx in the stratosphere as a result of N_2O photochemical degradation (Ravishankara et al. 2009).

Modification and Acceleration of the Composting Process

Biochar is not consumed in the composting process, and it has been noted that it appears to modify the composting process in as yet inexplicable ways. One hypothesis suggests that biochar provides habitat for microorganisms within its pore structure (Zhang & Sun 2014; Gang 2018). One aspect relevant to commercial composters is that biochar accelerates the active composting phase. This acceleration has been noted for turned windrows at California facilities (Rick Wilson, Agromin Inc. and Josiah Hunt, Pacific Biochar, personal communication). For turned windrow systems, accelerating the active composting phase increases facility throughput and thus has economic value. Biochar has also been perceived to help the composting process during seasonally wet conditions (Josiah Hunt, personal communication). Benefits of biochar have also been noted for aerated static pile composting. Preliminary data from an Agromin Inc. facility shown below (Figure 7.4) suggests biochar accelerated composting for negatively aerated static piles. In this case, 6% biochar by volume (Rogue Biochar, Oregon Biochar Solutions) was added and the maturation level of the compost was followed as determined by the Solvita index once per week. For this facility, an index of 6 is indicative of a compost that has gone through its active composting phase. The addition of biochar rapidly accelerated the composting process for this facility.

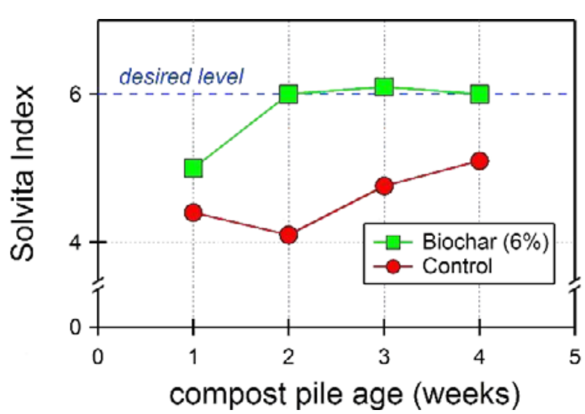

Figure 7.4. *Example of the impact of biochar on composting time for a commercial facility in California (Courtesy of Rick Wilson, Agromin Inc.)*

Another observed improvement is an increase in humus formation. The addition of biochar is thought to improve the composting process by acting as a support structure for microbial growth (bio-colonization). This enhances organic matter degradation, increasing the production of humic acids. Production of humic acids is also aided by biochar's role as an ion exchange material for sorption of ions (Kammann et al. 2015; Sanchez-Monedero et al. 2018). The increase in humification produces a better quality compost that is more stable in soils (Senesi 1989; Senesi & Plaza 2007). For example, Yu et al. (2019) followed the concentrations of humic and fulvic acids in a compositing trial with straw biochar and pig manure for different biochar additions of 1-10% by wet weight. Piles with greater biochar content displayed higher concentrations of these compounds over time. The presence of biochar appears to modify organic matter formation in the composting process yielding a better soil amendment. Operators at commercial compost facilities in California using biochar have also noted improved appearance of the compost (Josiah Hunt, Pacific Biochar, personal communication), likely reflecting the same processes.

Reduction in Gas Emissions

A growing number of reports of co-composting with biochar have noted that the presence of biochar reduces gas emissions from the composting process, most notably NH_3 and the GHGs N_2O and methane (CH_4) (Sanchez-Monedero et al. 2019). Significant reductions (47%) in NH_3 volatilization have been reported when 3% biochar by volume was added to poultry litter (Steiner et al. 2010), and a 30% reduction was observed when 10% biochar by volume was co-composted with poultry manure (Agyarko-Mintah et al. 2017). These results suggest biochar addition could also reduce NH_3 volatilization losses in composted cow manure. Wang et al. (2013) reported a 25% reduction in N_2O emissions from pig manure when co-composted with 3% biochar by volume. Collins et al. (2020) found that biochar at 20% and 40% (by volume) reduced nitrogen loss by 7.5% and 15% compared to the control. Collins et al. found that following active composting, control piles contained more ammonia and biochar-containing piles contained more nitrate. Godlewska et al. (2017) proposed the enhancement of ammonium (NH_4^+) oxidation rates to NO_3^- by nitrifying bacteria is the mechanism for reduced nitrogen loss in co-composting. The mechanistic details of the biochar / microbe / nutrient interaction are still not well understood.

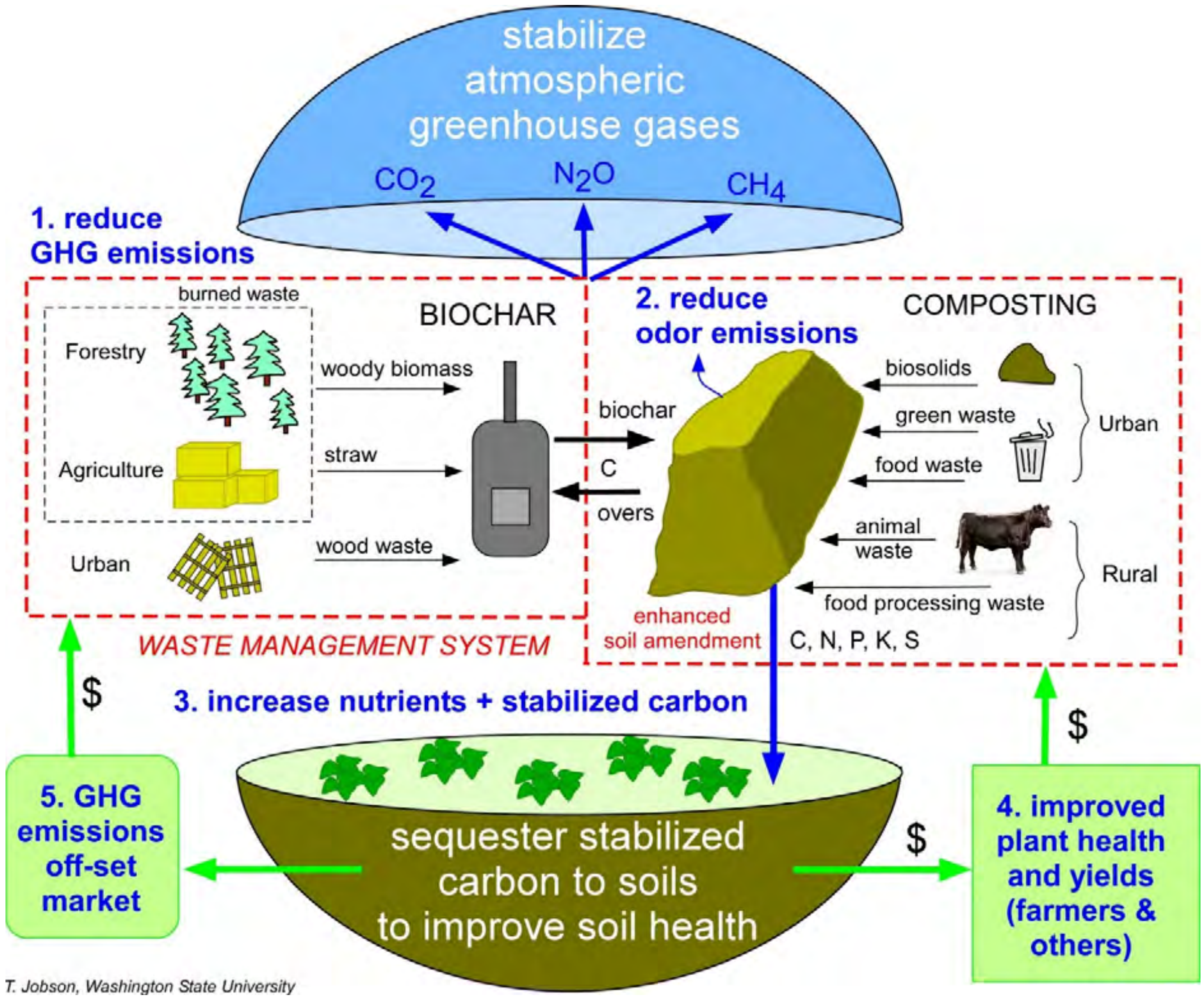

Figure 7.5. *Incorporation of biochar in composting operations can yield multiple benefits.*

While most of the experiments noting reductions in gas emissions have been done at small scale, Vandecasteele et al. (2016) reported significantly reduced CH_4 emissions for a commercial scale pile using 10% biochar by dry weight co-composted with a mix of green waste and the organic fraction of municipal solid waste. Cumulative emissions of CH_4 were reduced by 95%, while for N_2O a 14% reduction was observed over 90 days of pile aging. It is important to demonstrate the benefits at full scale commercial facilities as the impact of biochar on emissions is likely variable due to differences in materials and process conditions (e.g., temperature, pH, oxygen levels). To summarize co-composting benefits, Figure 7.5 illustrates how biochar production could be integrated into both urban and dairy waste management systems to capitalize on the noted benefits of co-composting with biochar. Additional revenue streams are possible for the waste management systems through carbon offset markets and production of a more valuable soil amendment for urban landscaping and commercial agriculture.

Reduction in Volatile Organic Compound Emissions

The composting process can emit a wide range of volatile gases, some of which have unpleasant odors, and the emissions of odors and volatile organic compounds (VOCs) can be a regulatory issue in compost facility permitting (Jobson & Khosravi 2019). Reductions in odor compounds and VOCs emitted during composting have also been noted in studies of co-composting with biochar (Steiner et al. 2010; Hwang & Lee 2018; Sanchez-Monedero et al. 2019). Addition of biochar may be a means of helping reduce odor issues from compost facilities and be a benefit to operators, though Hwang & Lee (2018) noted that different chars had different capacities for removing odor-causing sulfur compounds.

Measuring VOC emissions rates for commercial scale composting has not occurred widely due to the cost and complexity of sampling. Emissions from the surfaces of compost piles are typically measured using a surface flux isolation chamber—an approach used to determine VOC emission rates from several California facilities that utilize static windrows (CARB 2007; CARB 2015). There are also significant challenges in measuring emissions from large piles because of the wide variability that can exist in surface emissions rates. This variability in surface emission rates, obscures trends and makes comparisons between biochar treated and untreated piles difficult (Gang et al. 2019)

The complexities can be reduced by composting at smaller scales in the lab. An example of this is recent work conducted at WSU comparing emission from manure composts treated with biochar from Oregon Biochar Solutions (Jobson & Khosravi 2019). Approximately 400 lbs. (wet weight) of material was composted in two tanks: a tank with 10% biochar by volume and a control tank with no biochar. Emissions were continuously measured from the two tanks over two weeks. The tank with 10% biochar displayed lower emissions of some odorous sulfur containing gases such as dimethyl disulfide (DMDS) as shown in Figure 7.6. Addition of biochar may help control odor compound emissions at compost facilities, another potential benefit to composters.

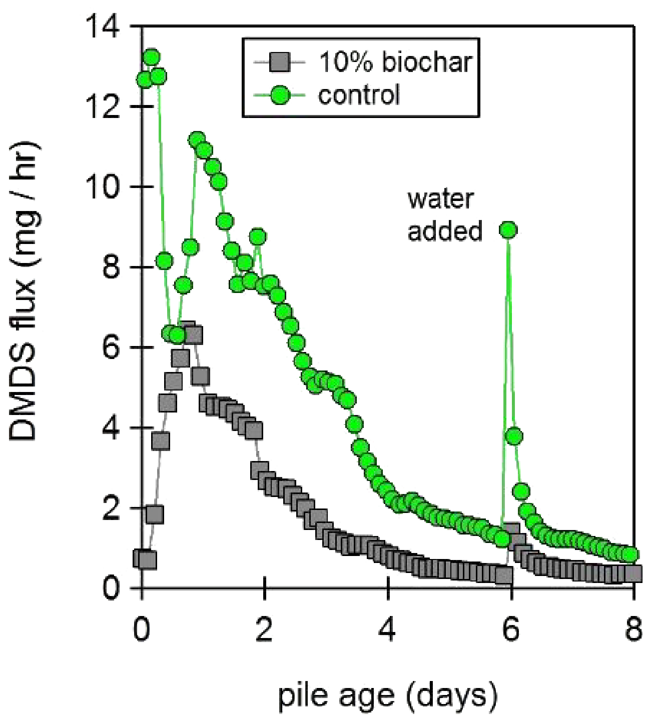

Figure 7.6. *Showing lower emissions of dimethyl disulfide from a 10% biochar co-compost of dairy manure (400 lbs. initial weight material) compared to regular compost. (Source: Jobson & Khosravi 2019)*

A clear recommendation for demonstrating gas emissions reductions when co-composting with biochar is to expand the research that has been done at commercial scale facilities so that real world composting conditions are documented. For facilities that use mechanical forced air flow aeration techniques, such as positive aeration, there are not clearly established methods for sampling. In lieu of finding the support of a cooperating commercial facility, a pilot scale composting plant, utilizing mechanical aeration processes, could be another valuable research facility.

GENERAL CONSIDERATIONS FOR COMPOST FACILITIES

Capacities and Equipment

Compost facilities in Washington and Oregon range from very small, processing only a few tons of materials each year, to quite large facilities processing hundreds of thousands of tons annually. In 2018, the smallest compost facility in Washington processed three tons of organics while the largest processed 235,000 tons. Just eight of these facilities handled 70% of all organics composted in Washington, and were able to because of their sizeable processing capacities. In general, large compost facilities already employ loaders, grinders, screeners, emission control systems, and other ancillary equipment that could also be used to operate a biochar production facility. The cost for this type of equipment can range between a few hundred thousand dollars to over a million dollars per facility depending on its capacity. Maintenance can range from a few thousand dollars a year to hundreds of thousands of dollars annually per piece of equipment. These capital and maintenance costs make co-locating composting and biochar production, and the consequent sharing of equipment and resources, extremely important to the financial feasibility of biochar production. Although facility capacity is just one of many factors to consider, the authors of this section see 50,000 tons per year as a minimum size for co-locating a commercial biochar production facility. At this scale, the facility is large enough to have the operating capacity and equipment to consider biochar production.

Location and Siting

The location of these large compost facilities is varied. In Washington, for example, two are located in rural areas in eastern Washington and six are located in rural or industrial areas in western Washington. The location of a compost facility can have a significant effect on how well a biochar facility might be suited for co-location. Zoning, ambient air quality, surface and ground water, surrounding land use, local population densities, availability of resources and utilities, and available organic residuals, are some of the conditions that need to be assessed to understand whether or not a biochar production unit may make sense at a compost facility.

SPECIFIC CONSIDERATIONS FOR COMPOST FACILITIES CO-LOCATING BIOCHAR PRODUCTION

Continuous feed pyrolysis significantly improves energy efficiency and reduces pollution emissions in comparison with batch kilns and seems well suited for compost facility operation. Pre-treatments and alterations in biochar production can generate "engineered" biochars to meet certain needs but would require the co-located site to maintain additional equipment or undertake additional processes. General information on biochar production is provided in *Chapter 11: Biochar Production*. The following factors should be considered specifically for biochar production at compost facilities.

Flow Through Rather Than Batch Processing

An additional unit process can be a significant impact to footprint of a compost facility. Batch processors require space and time to load, process, cool and unload. A flow through system, however, will require a minimum of space and the final biochar is produced in a single unit.

Biomass Pre-Treatment and Sizing

The flow through system should be capable of processing a wide range of feedstock sizes and shapes with minimal pre-milling or grinding. Current flow through biochar systems require homogenous feedstock (in size and geometry) to eliminate variations in dryness and VOC off-gassing.

Heating and Emissions Considerations

In order to create the lowest air pollutant emissions profile, the biochar production equipment should be designed to utilize the produced synthesis gases for the process heat to pyrolyze or gasify the biomass. Volatiles generated by pyrolysis are combusted by an afterburner, the heat from which can then be used to dry the biomass feedstock will yield the best carbon stabilization, with the most controllable emissions. In such a process the "flame" does not contact the biomass.

Tailoring Biochar Properties and Production for Co-Composting

Feedstock selection and pyrolysis temperature affect physicochemical properties of the final biochar product (Oliveira et al. 2017). Adjustments to the chemical environment during pyrolysis have been shown to affect char function and reactivity in the environment. Ayiania et al. (2019) demonstrated that with appropriate pre-treatment and pyrolysis with biochar produced in the presence of nitrogen and magnesium, both phosphate ion (liquid systems) and sulfur compounds (gas emissions) can be reduced. Other researchers have shown that biochar can be functionalized both with direct chemical and thermal processing and with exposure of biochar to other gases and steam treatment. For example, addition of air during biochar production (Suliman et al. 2016) or exposure to ozone following pyrolysis (Kharel et al. 2019) can add oxygenated functional groups and increase cation exchange capacity. There is great potential for the design and production of engineered chars, but there has been little systematic development in this area.

Co-located compost and biochar facilities could include processes to further activate, or functionalize the char, yielding engineered biochar with properties desirable for co-composting or specialty biochar markets.

Sizing

Finished biochar can be sized for appropriate uses with simple rollers or crushers requiring a minimal capital and footprint cost for use either within the composting operation for co-composting or sold as biochar into specific markets.

PERMITTING COMPOST FACILITY BIOCHAR PRODUCTION

A consistent issue across biochar production regionally is the permitting of a particular technology and facility. Biomass conversion to biochar has often been accomplished using open burning techniques. This has given regulatory agencies the incorrect perception that this is the only technology available for manufacturing biochar. In reality, there are a multitude of technologies available to create biochar, each with its own positive and negative attributes. To mitigate regulatory issues, technologies that minimize regulated emissions during operations should be prioritized. The challenge to the commercial biochar sector is also to produce and implement testing and assessment methodologies that clearly demonstrate the emissions outcomes, carbon stabilization outcomes, and GHG reductions for any pyrolysis process.

Biochar production technology and its understanding among regulators and potential biochar production facility owners is a barrier. Until regulators better understand the various biochar production technologies and their differences with respect to emissions, permitting will be complex. Until potential facility owners better understand the attributes and deficiencies of the process investors will be hesitant.

There are a variety of factors that will drive regulatory requirements. The size and location of the facility, feedstock designation, site land use zoning and permit structure, regulating jurisdiction, and local environmental conditions, are some of the major considerations that need to be identified and assessed. Depending upon these conditions, sites may require air permits, storm water permits, state waste discharge permits, solid waste permits, conditional use permits, and other environmental review. Conditions for these other permits can be highly variable depending upon location, regulatory authority, and scope of the project. A thorough assessment of these conditions is beyond the scope of this report. However, the air permitting process is further detailed in *Chapter 12: Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems*.

BIOCHAR PRODUCTION BEYOND THE COMPOST FACILITY: BIOREFINERIES

We have discussed the benefits of co-locating biochar production with a compost facility, both from the perspective of efficiently utilizing woody biomass, and for the potential benefits of co-composting with biochar. However, coupling more than these two technologies to further optimize valorization of organic waste streams is a primary motivation of the biorefinery concept developed by a range of researchers (Bell et al. 2014; Mountraki et al. 2016; Jungmeier et al. 2014). Washington State University researchers have proposed a regional solid waste handling biorefinery (Figure 7.7). The biorefinery emphasizes the synergistic use of technologies beyond composting to effectively treat specific organic waste streams while maximizing co-product generation and providing environmental benefits (e.g., local fertilizer production, GHG emissions reduction).

A similar idea for a centralized biomass center could provide a way to test and verify the processing capabilities of new biochar processors. The facility would need be located near biomass sources, and have the necessary truck and rail transport access, and access to grid power This center is proposed to investigate new technologies appropriate at different scales and test their capacities to reduce emissions and produce stable carbon with various functionalized configurations.

STRATEGIES TO OVERCOME BARRIERS

Perceptions and Marketing

Economic barriers associated with capital and operating costs will not be overcome until more full-scale facilities are built and become successful at selling their products. Successful marketing of biochar will be dependent upon how customers "view" or "feel" about the product and the general understanding of the benefits of biochar. An effective action that can be taken at this time is to develop market-level literature that educates the general public on the virtues of biochar use. This would be effective in an urban or suburban environment, particularly in cities that have food waste recycling programs. Markets exist for lawn and garden products where biochar and co-composted biochar products could be sold and provide a means to educate the public.

Regulatory and Societal

Regulatory barriers are complex and varied but the most prominent issue is air permitting. Producing unambiguous technology descriptions that define regulatory categories associated with biochar production technologies is the most effective action that can be taken at this time. These descriptions would need to fit into the regulatory categories of the National Emission Standards for Hazardous Air Pollutants for Source Categories (40 CFR Part 63) and associated rules.

Technology acceptance barriers by regulators will be partially overcome by using syngas to power biochar production, as this would lower overall process emissions. Standardization of emissions quantifying and reporting for each technology will allow for comparison by regulators and other interested parties. Further acceptance will occur when working facilities are more prominent. Acceptance by potential facility

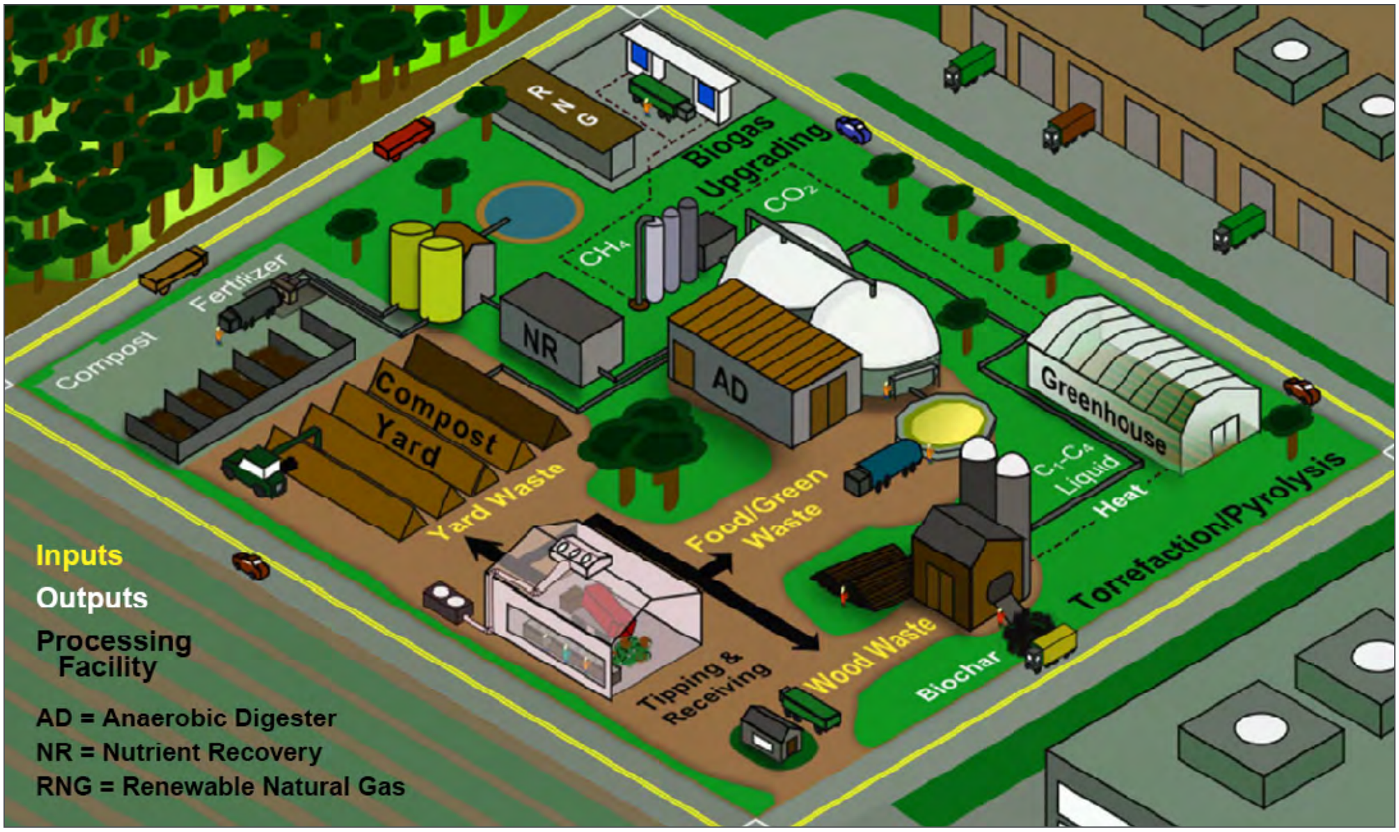

Figure 7.7. *The biorefinery concept for processing organic waste (Source: Hills et al. 2019).*

owners will also be partially overcome through wide-spread use. The most effective action that can be taken at this time is to have regulatory agencies do reviews of technologies and provide guidance documents that indicate potential acceptance of technologies or process conditions. This is likely to make potential facility owners more interested in pursuing this type of business opportunity.

Regulatory agency review and acceptance will also serve to help overcome societal acceptance barriers. Research and educational institution trials are also a method of creating social acceptance.

SUMMARY OF RECOMMENDATIONS

The benefits of co-locating biochar production with compost facilities are both environmental and economic. In order to overcome the regulatory, economic, and public perception barriers of biochar, we make the following recommendations:

1. Accurately identify and quantify emissions during biochar production (see *Chapter 12, Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems* for more background information):
   - Conduct a thorough review of air quality permit issues and recommendations for biochar production systems, monitoring, and emissions tests.
   - Develop a near term case study on biochar production that is not based on regulatory identification as incinerators, but as a separate category (e.g., biomass thermal treatment). In the longer term advance a proposal to establish a new category of permitting "carbon stabilizers" based on significant advances in design, operation, and monitoring. These would both be supported by thorough monitoring and testing to demonstrate emissions outcomes carried out on any apparatus.
   - Include criteria air pollutants (particulate matter, carbon monoxide, sulfur dioxide, nitrogen dioxide, ozone forming constituents) and other regulated volatile gases in air emissions research on biochar production. Emissions of GHGs will also be important to support life cycle analysis of biochar production. This is needed to support the air permitting process.

2. Conduct comprehensive studies into the attributes of biochar and co-compost and its end uses.

   - Characterize biochar adequately in research. Standardize biochar attributes with a common set of metrics. International Biochar Initiative (IBI) standards should be followed at a minimum, including reporting feedstock materials, moisture content, pre-treatment, pyrolysis process and temperature. Many papers report the study of biochar in a particular setting without discussion of the biochar properties.
   - Develop a research program to thoroughly understand biochar characteristics and functional properties that reduce compost emissions by capturing valuable nutrients (i.e., nitrogen, phosphorus, sulfur), reducing environmental impacts from leaching and gas emissions. This would also improve compost nutrient quality.
   - Support field research that evaluates biochar and co-composted biochar in soil end use settings. This could be undertaken in conjunction with or separately from the ten year multi-site research effort proposed in Chapter 3.
   - Support near-term research into the uses of biochar and co-composted biochar in field trials in the Pacific Northwest with various crop and soil combinations.

3. In conjunction with the National Renewable Energy Laboratory (NREL) and universities, develop a comprehensive capability to use computer models to evaluate biomass to biochar production systems and outcomes at three scaled levels: load-fed kilns and pyrolyzers, moderate-scale on-site pyrolyzers/gasifiers, and central facility gasifiers/boilers.
4. Provide systematic and ongoing biomass to biochar production process equipment design, engineering, and monitoring support at all levels of biochar production to meet the goals of lowest possible emissions and highest possible biochar production efficiency at minimum cost through a combined research and commercialization effort.
5. Establish a regional bio-processing center (biorefinery) in which composting is the primary organic fraction of municipal solid waste treatment, but that also has ancillary treatment processes and the capacity to test various biochar production systems.

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CHAPTER 8:

Agricultural Use

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SCOPE

Biochar has potential to reduce the environmental footprint in nearly every aspect of agricultural production. The use of biochar has been proposed to manage agricultural biomass (Stavi 2013), to process animal manure and poultry litter (Shakya & Agarwal 2017), to improve the nutritive value of feed (Man et al. 2021), and to mitigate the offsite movement of pesticides (Kahlid et al. 2020; Liu et al. 2018; Khorram et al. 2016) and soil nutrients (Gao et al. 2019; Figure 8.1). The coproducts of biochar production hold similar potential. For example, on-farm production of biochar can provide bioenergy to heat greenhouses and barns and to power farm equipment (Phillips et al. 2018). Pyroligneous acid, a coproduct of pyrolysis, has the ability to control fungal pathogens and deter pathogenic insects (Grewal et al. 2020). Although these environmental benefits are potentially substantial, their on-farm use has not been widely studied. Furthermore, the on-farm installation of biochar production facilities presents challenges that reduce the feasibility of co-production scenarios (Phillips et al. 2018).

Figure 8.1. *Agricultural biomass associated with orchard management (left) can be achieved by generating biochar that can be used onsite. In the right photo, biochar from orchard waste is applied to a commercial orchard in central Washington during tree planting to improve soil health. (Photos: Jeff Theil [left] and David Drinkard [right]).*

* *These authors contributed equally to this work.*

Table 8.1. *Biochar attributes supporting a prescriptive approach for biochar use in cropping systems.*

Biochar attributes	Type of biochar needed	Application rate/frequency
Liming/pH adjustment	High ash (>600 °C, high-ash feedstock).	As needed; calculated by pH of soil and neutralizing strength of char.
Rebuilding eroded soils	Large particle size (high coarseness) to improve infiltration.	Can be calculated from properties of soil + char and desired goal (e.g., porosity or water holding-capacity).
Reduced nutrient leaching	Large particle size (high coarseness) to improve infiltration and reduce runoff.	Annual.
Reducing disease pressure	Pre-conditioning of biochar may be needed for some applications (e.g., to reduce soilborne diseases in horticultural media) to allow time for biochar to impact microbial communities.	After germination. Variable. Frenkel et al. (2017) seems to say that lower application rates (<3% by volume) are needed for benefits relating to soilborne diseases (foliar diseases are somewhat less sensitive to higher application rates).
Residue management	On farm gasification or pyrolysis of residues, returned to the soil.	Annual trimming/harvest season.
Water retention	High temperature, oxidized for highest porosity.	As needed to achieve soil water holding capacity around roots.
Growth Stimulant	Insufficient data.	High application rate (<25% by volume) or injection with seed.

Recent recommendations regarding optimum biochar application rates for wood-origin biochars (2-5% by mass) and manure-origin biochars (1-3% by mass) (Guo 2020) translate to quite high application rates of 11 tons ac^{-1} (1%) to 57 tons ac^{-1} (5%), assuming an average bulk density. If implemented, such application rates will create an enormous demand for forest and agricultural biomass. As such, land application uses of biochar is likely to be an important driver for the scaling and development of biochar production systems.

Because land use application of biochar is widely studied, and because it has the potential to create a tremendous demand for biomass and biochar-based products, this section primarily addresses the application of biochar to agricultural soils.

NEED STATEMENT

Across all agricultural systems, a primary goal is to intensify production to supply food, fuel, and fiber to a growing global population. However, accomplishing this goal is increasingly difficult as soils become less productive, land area shrinks, and natural resources become more limited. At the same time, there is a growing public and regulatory demand for farmers to ameliorate the adverse environmental impacts of farming and to provide ecosystem services. The simultaneous and sometimes conflicting needs to improve crop yields while reducing chemical inputs, limiting greenhouse gas emissions, protecting water resources, and sequestering carbon can be achieved by improving soil health (Wheeler & Von Braun 2013).

Biochar is one important tool that has the potential to alleviate soil health deficiencies (Figure 8.2) and enhance ecosystem services by increasing soil pH (Phillips et al. 2018; Machado et al. 2018), improving tilth (Deluca & Gao 2019), increasing water holding capacity (Omondi et al. 2016; Razzaghi et al. 2020; Edeh et al. 2020) , decreasing the off-site movement of nutrients and pesticides (Kahlil et al. 2020; Liu et al. 2018; Khorram et al. 2016), and sequestering carbon (Liu et al. 2016; Bai et al. 2019; Matuštík et al. 2020). Biochars have a tremendous range in physical and chemical properties. The physiochemical properties of biochar are shaped by the nature of the feedstock, the parameters of production, and post-production treatments and processes. Therefore, biochars can be engineered to have specific attributes. Because biochars can be tuned to meet agronomic goals, prescriptive approaches that use engineered biochars to address specific soil deficiencies are possible. For example, farmers in some parts of the inland Northwest have a growing need to raise the pH of soils. Biochar that is high in ash and has a large calcium carbonate equivalence could potentially meet this need (Phillips et al. 2018). Likewise, farmers who use deficit irrigation could apply biochars to extend water holding capacity and alleviate intermittent water shortages. In order for farmers to adopt biochar-based practices, a deeper understanding of how production parameters determine biochar properties is necessary, as illustrated in Tables 8.1 and 8.2. (See end of chapter for Table 8.2).

Figure 8.2. *Outside of Spokane, Washington, wheat growth is dramatically increased in soil amended with biochar (8 tons per acre, right inset), compared to that grown in unamended soil (left inset). (Photo: Kristin Trippe)*

The impacts of biochars on soils and plants cannot be predicted from the properties of biochars alone, but also depend on how the biochar reacts with the soil, the crop, and the climate. This complexity has led to an enormous proliferation of biochar-based research publications. Despite the proliferation of the scientific literature that addresses biochar-soil, biochar-plant, and biochar-climate interactions, we are only beginning to disentangle the complexities of biochar-based amendments. As a result, few generalizable principles have emerged and biochar-based practices have not been widely adopted. In order for adoption to occur, it is paramount that farmers have the ability to predict, with reasonable accuracy, the agronomic responses to biochar applications. This ability can be achieved through the development of robust biochar-cropping systems models that are capable of predicting agronomic outcomes of biochar applications.

Robust biochar-cropping systems models are also needed to predict the environmental response to biochar application. Emerging policy initiatives that incentivize the removal of carbon from the atmosphere are currently under development. However, allocating carbon credits for soil biochar applications will require a means of estimating the long-term impact of biochar applications on net greenhouse gas emissions based on full lifecycle analysis. Direct measurement of changes in soil carbon stocks and greenhouse gas emissions at the field and farm scales is not practical, as the cost of such measurements would exceed the value of the carbon credits. Hence, computer models can be an important tool for assigning carbon credits to individual farmers based on estimates of the long-term impact of specific practices on net greenhouse gas emissions. Policy development and implementation would be strengthened by robust biochar-cropping systems models that are capable of predicting environmental outcomes of biochar applications, including estimates of carbon sequestration.

Resolving knowledge gaps and using that knowledge to build cropping systems models will substantially remove the barriers to farm-scale adoption of biochar-based practices. To accomplish this, we have developed five recommendations for implementation on the national and regional scales: *1) Establish a coordinated national scale network of long-term biochar field trials; 2) Develop a well-integrated biophysical modeling effort for application of biochar to agricultural soils; 3) Develop macroeconomic models to provide information relevant to national and sub-national policymaking; 4) Cultivate a prescriptive approach for utilization of biochar in regionally focused, cropping system specific niches; and, 5) Collaborate on regional techno-economic analyses that point towards most likely regional pathways for biochar production and use.*

RECOMMENDATIONS

Recommendation 1: Establish a coordinated national scale network of long-term biochar field trials.

We propose that the deployment of a coordinated, nationwide effort aimed at filling knowledge gaps will sufficiently lower adoption barriers by delivering decision support tools and providing prescriptive recommendations that allow farmers to improve soils and achieve agronomic goals. The coordinated effort will entail an iterative approach that uses data from long term field trials to develop, calibrate and validate agroeconomic models that can predict agronomic and environmental outcomes on local and regional scales. The outcome of the models will, in turn, inform the direction of long-term studies and prompt short-term studies to address emerging questions. The effort will be coordinated, implemented, and assessed by a network of scientists that are charged not only with conducting the research but also with consolidating and curating data in such a way that it is applicable and available to complementary investigations. Figure 8.3 outlines the structure of the proposed network. We anticipate that, through this network, a deeper and more comprehensive understanding of biochar will emerge. As such, generalizable principles that can be translated into

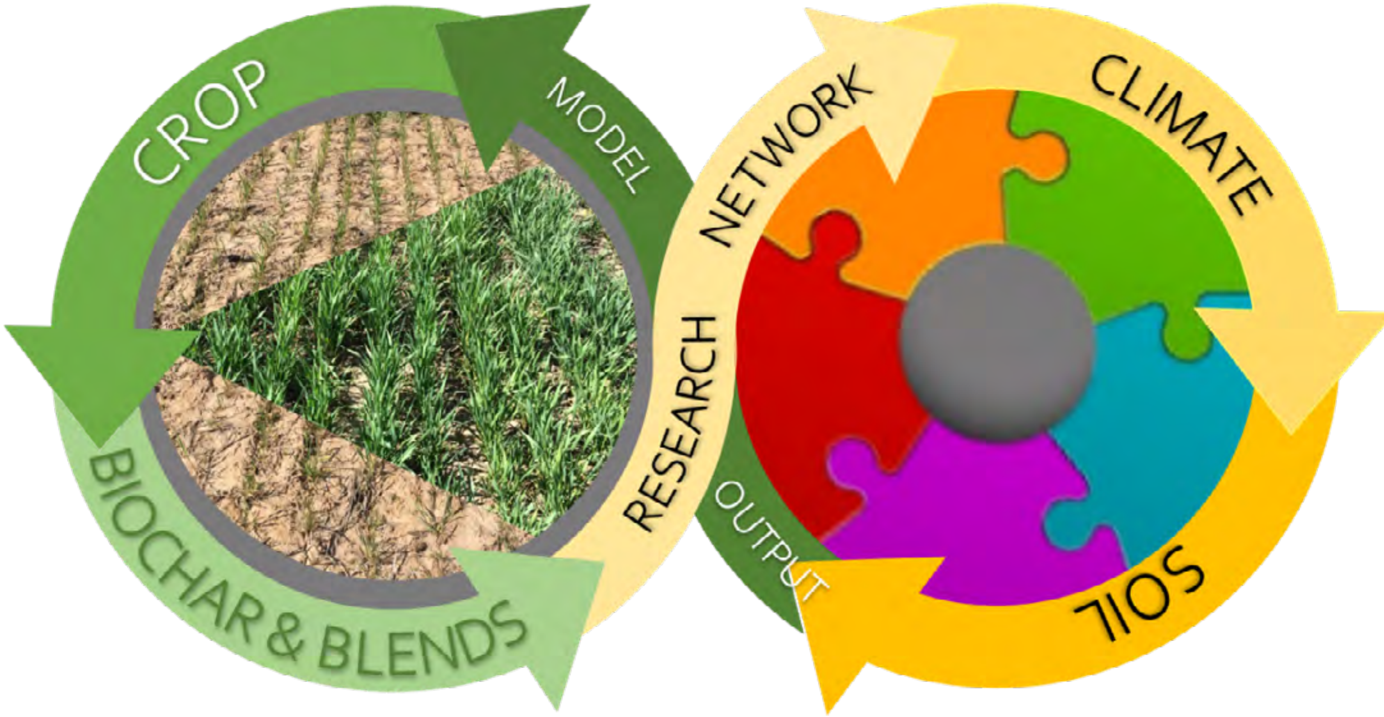

Figure 8.3. *Structure of proposed network. (Credit: Kristin Trippe)*

decision support tools, best management practices, and extension guidelines will be developed.

Research Objectives

The lack of extension recommendations regarding agronomic outcomes of biochar application at the field-scale are due to sizable knowledge gaps. Specific research questions regarding the effects of biochar on crop outcomes include: 1) the response of plant growth and crop yield to different biochar types across different climates, soil types and management systems; 2) the influence of physiochemical properties of biochar on crop nutrient use efficiency and nutrient leaching for different climates, soil types and management systems; 3) the mechanisms by which biochar improves soil health deficiencies; and, 4) the effects of biochar on system resilience in response to extreme climate events. Closing these gaps, as well as determining agronomic techniques for applying biochar (rate, timing, method) will allow researchers to develop and disseminate best management practices and extension recommendations.

While the lack of biochar adoption is due to uncertainty regarding the influence of biochar on crop outcomes, it is also due to prohibitive costs and uncertainty about return on investment. Because biochar can provision ecosystem services, policy incentives should be developed to support the implementation of the practice. The most obvious and clear case for policy incentives is based on the ability of biochar to capture and store carbon. Although several studies have examined the potential for biochar to store soil carbon, salient questions need to be addressed prior to the development of policy incentives. These questions include: 1) quantifying biochar-microbial interactions that lead to changes in carbon mineralization rates, and the effect of these changes on soil organic carbon stocks across different climates, biochar types, soil types and management systems; and 2) quantifying the effects of different biochar types on changes in soil organic carbon stocks and greenhouse gas emissions across different climates, soil types and management systems. In addition to capturing carbon, biochar also has the potential to provide other agroecosystem services, including improving water quality by reducing off-site migration of nutrients and pesticides and decreasing erosion and runoff. However, policy incentives regarding nutrient management and water quality are more difficult to measure and quantify. As such, questions that inform policy should initially be focused on quantification of carbon capture and storage.

Results obtained from strategically designed long-term field trials have the potential to provide answers regarding the agronomic and environmental outcomes of biochar application by closing the identified knowledge gaps. To accomplish this, we propose that a national network of long-term biochar field trials should be established in at least ten locations across the U.S. At these sites, which should be chosen to represent diverse soil types, cropping systems, and climates, researchers will conduct coordinated studies using a common set of biochar types, management practices, and research protocols. Each field site would yield a common minimum data set including soil physical and chemical properties, soil respiration, crop and biomass yields, and changes in soil organic carbon stocks. The field trials would be maintained for a minimum of ten years to provide long-term biochar response data. A national database of results from these field trials will be developed that can be used to robustly calibrate and validate the biochar agronomic and environmental models. In addition to these ten long term biochar research (LTBR) plots, diverse regional efforts addressing cropping system-specific questions using local management practices and feedstocks applied to economically-important crops efforts would support LTBR efforts by collecting and contributing the minimum dataset using established protocols (Figure 8.4). In return, these efforts would receive support letters, assistance with data interpretation, and the ability to store data using LTBR resources. In addition to closing knowledge gaps regarding biochar effects, the establishment of LTBR field trails coupled with regionally-specific trails will ensure that experimental results of LTBR efforts are translatable and that recommendations that emerge from the LTBR network are applicable to local cropping systems.

Figure 8.4. *Ongoing regional experiments could help ensure that experimental results from a national network are translatable to local cropping systems. The potato plants shown here are part of a Washington State University and Department of Ecology research field trial that evaluated potato production following amendment with a regionally produced biochar, co-composted biochar and compost. The darker colored, four leftmost rows illustrate the effects of fertilizer on potato biomass. (Photo: Steven Seefeldt)*

To coordinate the LTBR and the regionally-specific research efforts, a structured network of scientists must be organized to integrate efforts that generate hypotheses, establish protocols, manage data, and direct research deliverables in the form of publications and recommendations. Additionally, the network will create and coordinate efforts to archive biochar samples, create and manage data that describe biochar properties, and provide guidance to individual LTBR and related researchers on the handling and storage of soil and plant samples. Collectively, these efforts will generate iterative work that will describe mechanisms through which biochar has impact. There are several examples of existing research networks that function similarly. The framework established by the Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) is an excellent model on which to establish a biochar-based research network. Within GRACEnet, research and geospatial data are collected with established protocols that ensure that results are comparable across GRACEnet locations. Points of contact upload data into accessible data repositories for incorporation into models and greenhouse gas inventories to produce actionable recommendations. The formation and cultivation of a similar network composed of biochar-based researchers would similarly contribute data to help develop and train models (see Recommendation 2) to better predict agronomic responses and environmental impacts.

Recommendation 2: Develop a well-integrated biophysical modeling effort for application of biochar to agricultural soils.

We propose that the development of models that can reasonably predict agronomic and environmental outcomes of biochar application will lower barriers to the adoption of biochar-based practices by providing reliable information to researchers, extension agents, crop consultants, and farmers. However, to accomplish this, models must be able to address the diversity of biochars, soils, climates, crops, and management systems. Likewise, the models must be scalable and function at the pedon, field, regional, national, and ultimately global scales. Furthermore, these models must have the ability to predict, with reasonable accuracy, crop and biomass yields, leaching of nutrients, emissions of greenhouse gases and changes in soil physical, chemical and biological properties for diverse biochar types, soil types, climates, crops, and management systems. In order to design and implement biochar-based models that accommodate diverse systems on a broad spectrum of scales that have accurate output regarding multiple parameters, several knowledge gaps must be addressed. *Specific knowledge gaps that limit the development of robust biochar-cropping systems models include: 1) biochar quality parameters; 2) priming* *effects of biochar; 3) biochar-soil-crop-climate interactions; 4) biochar impacts on autotoxicity and plant disease; 5) plant hormonal and toxin effects of biochars; 6) effects of different types of biochar; and 7) biochar management systems.*

Biochar quality parameters

Biochar models need input parameters to characterize biochar properties. The parameters need to be readily measurable properties of biochars that characterize the diversity of biochars and maximize the ability of the models to predict agronomic and environmental outcomes. For example, most biochar models assume recalcitrant and labile biochar carbon pools. To predict the fate of biochar carbon in soils, model inputs need estimates of both the size and half-lives of the labile and recalcitrant pools. These properties, however, cannot be measured directly except through long-term and expensive incubation studies. Readily measurable parameters, such as hydrogen to carbon (H/C) ratios, volatile matter, potassium permanganate ($KMnO_4$)-oxidizable carbon, and hot-water extractable carbon, need to be developed and calibrated to serve as proxies for estimating the size and half-lives of the labile and recalcitrant biochar carbon pools. Other biochar quality parameters are needed to predict the impact of biochar amendments on soil cation exchange capacity, bulk density, porosity, drainage, plant available water, nutrient cycling, and microbial activity.

Priming effect of biochar

Biochar may impact the rate of mineralization of native soil organic matter when it is added to soils through what is often referred to as a 'priming' impact. In the literature, biochar has been reported to cause positive, negative, and neutral priming of biogenic soil organic matter mineralization. Understanding both short-term and long-term priming effects of biochar in different soils under different climates and cropping systems is critical to predicting the long-term impact of biochar amendments on both soil carbon stocks and nutrient cycling. Existing biochar-cropping system models already have priming coefficients; but we need to know whether those coefficients should be positive, negative or neutral and whether they should be constant or change over time, biochar types, climates, soils, and management systems.

Biochar-soil-crop-climate interactions

Cropping system models are increasingly sophisticated in predicting crop responses to climate and management. Most such models include a limited set of soil parameters focusing primarily on the soil water and nitrogen cycling. Often soil pH, cation exchange capacity (CEC), bulk density, field capacity, and permanent wilting point are treated as constants and must be input to initiate the model. In reality, these parameters are dynamic and are influenced by climate, crop growth, and management (e.g., acidifying fertilizers, compaction caused by wheel traffic). Furthermore, biochar amendments alter these soil properties. Cropping systems models need to be revised to treat these parameters as variable and to account for biochar-soil-crop-climate interactions.

Biochar impacts on autotoxicity and plant disease

A growing body of mostly anecdotal evidence indicates that biochar amendments can reduce autotoxicity associated with decomposition of crop residues and can suppress some soil born fungal pathogens. These effects, when they occur, can have a substantial effect on crop yields, but are not currently included in cropping system models. Understanding these effects and being able to incorporate these into cropping systems models would greatly improve the accuracy of model predictions.

Hormonal and toxin effects of biochars

Biochars are known to release various organic compounds that influence plant growth and development. Which types of biochar release these compounds and whether these effects are short-term or persistent is unknown.

Effects of different types of biochar

Biochar quality varies substantially depending primarily on feedstock, peak pyrolysis temperature, and pyrolysis technology. To date most field research has been conducted using biochars produced from woody feedstocks by slow pyrolysis. The results from these studies may not be relevant for predicting crop response to biochars produced by fast pyrolysis from crop residues and herbaceous feedstocks. Field trials with diverse biochar types are needed to build robust models.

Biochar management systems

Field and laboratory research is needed to optimize biochar management options. For example, biochar can be uniformly applied in a single large surface application and incorporated by tillage; alternatively, biochar can be strategically applied on eroded hill tops or other problem soils. Biochar can be injected into problematic subsoils such as hard setting E horizons that restrict root growth or clay rich argillic horizons that restrict drainage. Various biochar-fertilizer formulations are under development that may or may not be effective for improving nutrient use efficiency in crop production. Acidified biochars can be banded with fertilizers proximal to seed placement to improve early season seedling growth and development.

Recommendation 3: Develop macroeconomic models to provide information relevant to national and sub-national policymaking.

A robust carbon negative pyrolysis-biochar-bioenergy industry will not develop without policy intervention. Without policy intervention, liquid transportation fuels produced by pyrolysis of biomass are not now, and are unlikely to be, cost competitive in the foreseeable future with liquid transportation fuels produced from petroleum. Under current policies, the environmental costs of petroleum and the environmental benefits of biochar and biofuels are both discounted. Future policies designed to address climate change will, in one way or another, put a tax on fossil fuels that penalizes the emissions of greenhouse gases and establish a carbon credit system that promotes the removal of carbon dioxide from the atmosphere. The design and development of effective policies will require macroeconomic models that can predict the impact of various policy options on the level of adoption of covered practices, energy prices, commodity prices, indirect land use effects, local and regional economies, and ultimately net greenhouse emissions. Detailed analysis concerning the types of macroeconomic models needed to facilitate policy development are beyond the scope of our discussions. However, cropping system models that predict the impact of biochar amendments on agronomic and environmental outcomes are critical tools that provide foundation for such macroeconomic models.

Recommendation 4: Cultivate a prescriptive approach for utilization of biochar in regionally focused, cropping system specific niches.

At the regional level, a prescriptive approach for utilization of biochar in regionally focused, cropping system specific niches is needed. By prescriptive, we mean an approach that is aimed at utilizing locally produced biochars as a strategy to address specific issues within regional crops and cropping systems. The approach should be informed by regional-level techno-economic analyses that point towards the most likely regional pathways for biochar production and use.

The prescriptive approach is essential because it focuses attention on those situations in which producers would be most likely to consider adoption if economics are favorable and concrete guidance can be developed. As an illustration of how this framework can be applied, Table 8.1 identifies different major impacts of biochar and describes the types of biochar and application rates that should be considered. Table 8.2 applies a prescriptive framework that marries knowledge about the potential impacts of biochars on soils with place-specific knowledge of specific agricultural niches in the Pacific Northwest where biochar may help overcome existing constraints to yield or quality in ways that may economically benefit growers. This approach focuses attention on the eventual biochar purchaser. It also emphasizes the need for ongoing biochar process/product development with the aim of producing biochars that can most effectively provide the desired attributes—though at present, it can be difficult to find biochar that is optimized for a particular use in quantities large enough to support field trials, due at least in part to the fact that current markets are not large enough to clearly support the commercial viability of such production.

Recent investigations of whether biochar could benefit blueberry production in the Pacific Northwest illustrate this approach (Sales et al. 2019). Blueberries (*Vaccinium* sp.) prefer well-drained acidic soils with high levels of organic matter. Organic amendments such as bark or sawdust are often incorporated into mineral soils before planting to increase organic matter and improve soil structure. These materials are expensive, and thus growers are interested in alternatives. Phytophthora root rot (associated with *P. cinnamomi*) can also be an issue for growers. Based on these needs, a greenhouse study explored the application of biochar alone (at 10% or 20% by volume), and biochar with bokashi (4:1 mix of biochar and bokashi produced from rice bran), to blueberry seedlings in two 12-week experiments. Bokashi was chosen because the fermentation process converts food waste to a nutrient-rich product that is low in pH and thus is likely to fit well within a blueberry system (whereas most biochars are high in pH, as is compost, another potential amendment). Plant growth was greater in soil with biochar than in unamended soil and there were also much greater levels of root colonization by mycorrhizal fungi. Biochar also appeared to improve soil aggregation but had relatively little effect on soil pH and plant nutrition and no effect on root infection by *P. cinnamomi* at the application rates used in this study. Addition of bokashi to the biochar improved plant growth and nutrition, particularly under nutrient-limited conditions. Based on these results, researchers plan to test biochar in a new field planting of highbush blueberry and to explore the best method and rate to apply it (Figure 8.5). Clarifying these factors will help the team to explore both effectiveness and cost, key to potential future adoption by growers.

Figure 8.5. *Graduate student Bryan Sales applies biochar to newly planted stands of blueberries in Aurora, Oregon. (Photo: Scott Orr)*

Generally speaking, the prescriptive approach is also informed by an awareness of the non-biochar management alternatives that producers are likely to consider, and the potential value-proposition of biochar in comparison to those other alternatives. It also responds when possible to potential regional biochar sources, in line with the concept of biochar "system-fit" (Sohi et al. 2015). As the ability to model the impacts of biochar application to cropping systems develops, this may also be used to identify additional opportunities that should receive further attention at the regional level.

Especially given the current lack of carbon policy incentives, regionally-focused approaches can be further informed by a preliminary assessment to determine particular cropping systems for which biochar can provide desired benefits at a cost that is reasonable. Several economic analyses have indicated that biochar's current economic benefits (in the absence of subsidies) exceed the cost of application only when applied to high value regional crops such as potatoes or diversified vegetables (Sessions et al. 2019; Garcia-Perez et al. 2019), whereas application to a wider range of crops (including dryland crops), becomes economically feasible only when financial policy incentives are available.

Work at the regional level will most likely take place along the discovery—application continuum (Figure 8.6). For biochar attributes that are less well understood (e.g., disease suppression), exploration of mechanisms will help develop understanding of where impacts are likely to occur. As promising prescriptive applications reach higher levels of technical readiness, field trials should emphasize demonstration and communication at scales that are relatable to farmers. Including analysis of the impacts on farm economics and profitability—across multiple years of a crop rotation and including impacts on economic risk reduction—will also help producers weigh the potential costs and benefits of biochar application. Communication of field-level results, development of use guidance, and decision support tools will all support eventual adoption.

Figure 8.6. *Stephanie Chiu and Sarah Light remove soil cores to test the response of soil water to biochar additions at a field trial site in Pendleton, Oregon. (Photo: Claire Phillips)*

We also propose that coordinating regional-level biochar field trials with the national research framework will maximize the knowledge gained from these regional trials in a number of important ways. First, by utilizing established data-collection protocols, it will ensure that data are comparable across sites. Second, it will focus attention on the collection of data most needed to advance the biochar biophysical modeling effort. Third, by connecting biochar researchers with each other and with the national network, it will raise the level of interaction and collective knowledge relating to biochar's impacts in agricultural systems, and thus the level of sophistication of individual regional efforts.

Recommendation 5: Collaborate on regional techno-economic analyses that point towards most likely regional pathways for biochar production and use.

Techno-economic analysis is critical for building a biochar-bioenergy industry. Whether focused on large centralized biorefineries or distributed on-farm pyrolysis units, building a biochar-bioenergy industry ultimately requires that pyrolysis plants be built at specific locations. For a specific pyrolysis plant to be economically viable, a local supply of feedstock, infrastructure to harvest, store, and transport the feedstock, and markets for the biochar and bioenergy co-product must exist and be accessible. Furthermore, life cycle analyses are needed to quantify energy and mass balances and net greenhouse gas emissions at the plant scale. Communication between agricultural researchers and those working on other aspects of techno-economic analysis is important to ensure that assumptions about the agricultural market size are reasonable. Cropping system models that predict the impact of biochar amendments on agronomic and environmental outcomes are also critical tools that inform techno-economic models about the potential market size for biochar co-products. Building regional biochar markets requires local on-farm research to develop solutions to local agronomic problems using locally available biochar resources.

CONCLUSION

The potential for biochar to benefit agricultural production and sustainability is substantial, but this benefit is not currently being fully realized. Further work is needed to disentangle the complexity of the interactions between the many types of biochar, soils, crops, and climate, and to develop generalizable principles. It is our feeling that a coordinated national scale network of long-term biochar field could elucidate the mechanisms of biochar's impacts in soils more efficiently than the current decentralized approach. Meanwhile, robust biochar-cropping systems models are also needed to predict the environmental response to biochar application. These models would also support developing policy initiatives to incentivize the removal of carbon through biochar, by providing a means to predict the carbon benefit of biochar application to soils.

At the regional level, a prescriptive approach for utilization of biochar should guide research efforts, in which biochar is explored as a potential solution to an identified problem for which growers are actively seeking solutions. By paying attention to the value proposition of biochar compared to other management options that are available to growers, as well as economic analysis to weigh costs and benefits, scientists have improved the likelihood of developing biochar application strategies that ultimately are meaningful to regional growers.

Table 8.2. *Examples of yield-focused, prescriptive uses for agricultural char.*

Issue addressed by biochar/ Example application in the PNW	Value proposition of biochar over other management alternatives	Potential regional sources of appropriate biochar	Technical Readiness Level	High priority research questions	Key Example References (Regional field results, when possible)
Liming from biochar can raise pH of acidic soils due to long-term use of ammonium-based fertilizers. Wheat-based dryland cropping systems (inland PNW).	Natural product. Can provide additional benefits over lime such as reduced aluminum phytotoxicity, improved soil moisture and permeability, and increased CEC. On the other hand, earlier analysis Biochar may not be cost-competitive with lime if only pH impacts are considered, but producers in many areas have not typically applied lime despite acidic conditions, so biochar may meet an unmet need.	If cost could be justified, biochar produced from poultry litter, which is high in ash and has a large calcium carbonate equivalence, could potentially meet this need, though transportation would add cost. Alternatively, to minimize cost, onsite residues could be used in areas where residue production is adequate. Combinations of biochar with other alkaline waste products (e.g., fly ash) have also been discussed and research is ongoing.	High	What is the long term neutralizing capacity of char? Can the long-term economic benefits justify the costs, and if yes, under what conditions? Approaches for reducing cost and labor for biochar production, spreading and incorporating biochar remain a challenge. Biochar from onsite residues will need to generate benefits that are competitive with alternative residue uses (e.g., baling and offsite sale of wheat straw).	Physical feasibility of biochar production and utilization at a farm-scale: A case-study in non-irrigated seed production. (Phillips et al. 2018) Alkaline biochar amendment increased soil pH, carbon, and crop yield. (Machado et al. 2018) Grass seed residue trials. Ag Energy, unpublished data.
Biochar can rebuild highly eroded "knobs" have much lower yield than surrounding areas. Eroded wheat-based dryland cropping systems (Palouse).	On-site residue use may provide an economically viable option in a cropping system with few cost-effective strategies existing (transporting other organics is cost-prohibitive).	Use of onsite residues could aid in economic viability, if costs can be kept low enough and biochar can perform well enough.	Low-Medium	Can increases in yields cover production/application costs in concentrated areas? What strategies prevent erosion from occurring again over time?	Influence of contrasting biochar types on five soils at increasing rates of application (Streubel et al. 2011).

Issue addressed by biochar/ Example application in the PNW	Value proposition of biochar over other management alternatives	Potential regional sources of appropriate biochar	Technical Readiness Level	High priority research questions	Key Example References (Regional field results, when possible)
Biochar can reduce nutrient losses from topsoil as nutrients run off fields, increasing production costs and environmental impacts. Grass seed grown on poorly drained soils/Willamette Valley. Acreage receiving repeated manure applications.	CEC adsorbs nutrients and porosity of char absorbs water - both effectively reduce nutrient leaching. Biochar is unlikely to be cost competitive with the alternative of no action. However, if changes are required to reduce nutrient losses, it may become cost competitive in some cases (e.g., requirement for reducing nutrient applications).	Use of onsite residues could aid in economic viability, if costs can be kept low enough and biochar can perform well enough.	Medium	What is the optimal application rate and schedule? What is the cost benefit calculation? Mechanisms need to be defined to inform biochar production parameters. more work is needed for specific soils and crops so that accurate results can be achieved.	Biochar impact on nutrient leaching from a Midwestern agricultural soil (Laird et al. 2010).
Biochar can reduce disease pressure from some high value crops in the PNW, with examples including nursery crops, potatoes, and small fruits. Soil-borne diseases in nursery crops and potatoes. Foliar diseases including Botrytis, Phytophthora and Powdery mildew in strawberries. Powdery mildew and late-stage diseases such as Fusarium in tomatoes (direct market production). Late-stage diseases in asparagus.	Natural, includes other benefits of biochar, may reduce pH of soil. Existing chemical strategies may be expensive and cause harm to workers. Pathogens may develop resistance to repeated fungicide applications. In addition to yield, crop quality is also often economically important, generating another avenue through which benefits can be realized. Economic benefits could also be realized by enabling maintenance or increasing the frequency of the highest value crop in the rotation.	Applications to these high value crops may be able to support higher biochar costs (and thus a wider range of biochar feedstocks and production systems) than other cropping systems—if benefits can be shown.	Low	Adding unconditioned biochar followed by infections with pathogens such as Rhizoctonia and Pythium can cause early stage diseases occasionally results in neutral or negative effects. Pre-conditioning stage should be incorporated as an important stage during biochar application in nurseries and soilless media, and possibly into soil.	Biochar as a management tool for soilborne diseases affecting early-stage nursery seedling production (Jaiswal et al. 2019). Activating biochar by manipulating the bacterial and fungal microbiome through pre-conditioning (Jaiswal et al. 2018).
Wood waste can be managed for disease control with biochar production, with reduced air quality impacts compared to open burning. Perennial tree fruit (central Washington and N central Oregon).	Air quality impacts of biochar should be lower than open burning for use with tree trimmings to be attractive.	Onsite	Med-High	What are the air quality impacts of charring trimmings compared to burning?	Apple orchards have been shown to benefit from char (Ventura et al. 2013).
Ag. residues can be turned into char rather than by using mechanical means in irrigated high residue annual cropping systems that break down quickly in the environment. Residue management for irrigated high residue annual cropping systems in the Basin.	Could result in higher persistence of residue, which may be beneficial in at least some irrigated high residue annual cropping systems.	Onsite	Med-High	How would a biochar strategy compare to other current strategies for managing residues in high residue annual cropping systems?	Charring is established as a management tool for management of residue in agro-ecosystems (Stavi 2013).
Biochar can retain water for growers who are deficit irrigating (e.g., coarse-medium texture soils). Deficit irrigated crops (e.g., wheat, N central OR) or high value crops grown without irrigation (e.g., diversified vegetables for direct markets in western WA and OR).	Provides amendment benefits in sandy/silty soils. Reduces irrigation requirements which is beneficial in situations where water access is limited for physical or regulatory reasons.	High coarse-textured char to increase retention in soil.	Low	Can biochar provide sufficient benefits in improved water holding capacity to be economically justified?	Can biochar conserve water in Oregon agricultural soils? (Phillips et al. 2020)
Biochar can be applied to soils for plants that require well-drained soils with high organic matter. Blueberries High-value irrigated crops	Wood chips/sawdust are often used to amend mineral soils prior to planting, but are expensive as they need to be replaced and don't generally result in higher yields. Biochar is more durable than wood chips and has shown benefits in greenhouse studies. Can be applied with compost utilizing the same distribution and application systems.	Application to blueberries requires a low calcium carbonate equivalence, coarse-textured char. Applications to these high value crops may be able to support higher biochar costs (and thus a wider range of biochar feedstocks and production systems) than other cropping systems—if benefits can be shown.	Medium Low	What application rates are appropriate? Can long-term benefits be demonstrated? Under what conditions) if any) can co-composted biochar or biochar + compost out-perform compost applications?	Amending sandy soil with biochar promotes plant growth and root colonization by mycorrhizal fungi in highbush blueberry (Sales et al. 2020). Integrating compost and biochar for improved air quality, crop yield, and soil health (Gang et al. 2019).

Issue addressed by biochar/ Example application in the PNW	Value proposition of biochar over other management alternatives	Potential regional sources of appropriate biochar	Technical Readiness Level	High priority research questions	Key Example References (Regional field results, when possible)
Biochar can replace vermiculite or perlite in potted/ greenhouse crops as a soil bulking agent and sometimes growth stimulant. Nursery crops (including cannabis).	More renewable than vermiculite or perlite. Marijuana wastes in at least some states are subject to additional regulations and cost regarding disposal, making onsite processing more attractive.	Applications to these high value crops may be able to support higher biochar costs (and thus a wider range of biochar feedstocks and production systems) than other cropping systems—if benefits can be shown. Production from greenhouse wastes may also be attractive in some cases due to existing disposal costs.	High	Cost benefit needs to be determined.	Substitution of peat moss with softwood biochar for soil-free marigold growth (Margenot et al. 2018). Effects of conifer wood biochar as a substrate component on ornamental performance, photosynthetic activity, and mineral composition of potted Rosa rugosa (Fascellaet et al. 2018). Influence of biochar, mycorrhizal inoculation, and fertilizer rate on growth and flowering of Pelargonium (Pelargonium zonale L.) plants (Conversa et al. 2015).

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SECTION III:

Supporting Information

This section provides further information to support earlier chapters of this report. This regionally relevant supporting information is focused on:

Chapter 9: Biomass Supply

Chapter 10: Biomass Handling

Chapter 11: Biochar Production

Chapter 12: Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems

CHAPTER 9:

Biomass Supply

Mark R. Fuchs, Deborah S. Page-Dumroese, and Karen M. Hills

Biomass feedstock for biochar production consists of three major categories: *agricultural biomass* (e.g., orchards or vineyard prunings, straw, corn stover, manure), woody materials from urban refuse disposal (e.g., clean woody construction debris, yard waste, materials from urban vegetation management; referred to in this report as *urban woody biomass*), and woody materials from vegetation or forest management outside of urban areas (e.g., forest harvest, wild fire fuel reduction, forest restoration, recreation maintenance; referred to in this report as *forestry biomass*)[1]. In some parts of the Pacific Northwest (PNW), agricultural residues are abundant, and urban woody residues represent an opportunity to tap into a waste stream that already has centralized collection (further detailed in *Chapter 7: Biochar Produced and Utilized at Municipal Compost Facilities*). While forestry biomass represents the largest potential waste stream from which biochar may be sourced, it is widely dispersed and must include assumptions that harvest operations occur in a sustainable manner in line with forest management objectives.

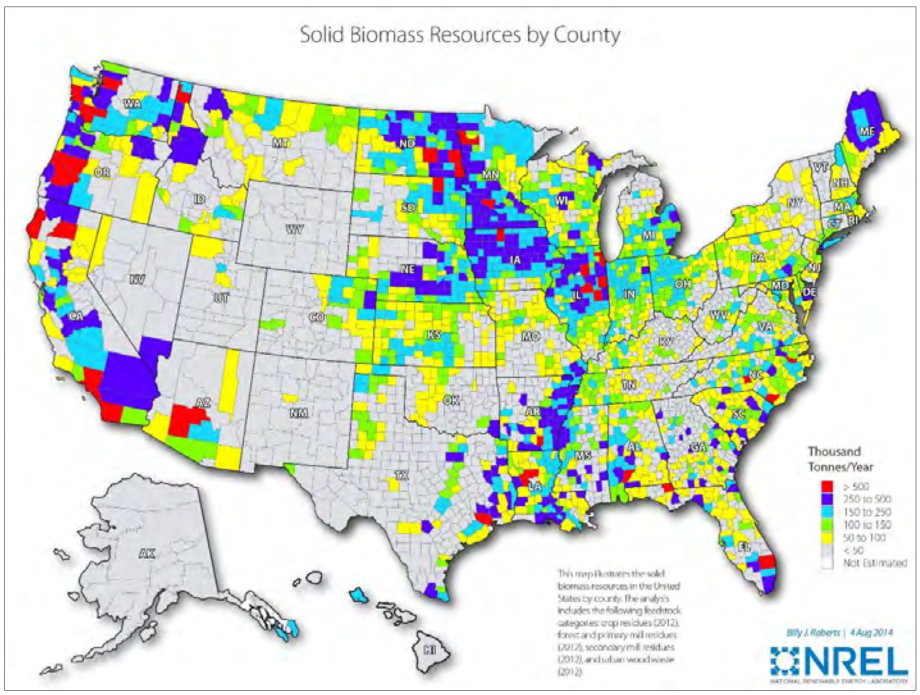

Figure 9.1. *A 2014 map of solid biomass resources by county across the United States including crop residues, forest and mill residues, secondary residues, and urban wood waste. (NASEM 2019)*

A summary of environmental, policy and regulatory considerations related to forestry biomass harvest is provided in Skog & Stanturf (2011).

Previous studies of biomass availability meant to inform bioenergy production can provide valuable information on feedstock for biochar. Numerous studies of both quantity and potential uses of forest harvest operations that create low- and no-value woody biomass have been conducted over the past 15 years. The PNW and western U.S. regions are relatively rich in biomass resources, offering potential for sustainable biomass harvesting that can provide feedstock for biochar production (Figure 9.1).

1 *For detailed information on characteristics of biomass feedstocks and impact on the resulting biochar, see Chapter 3 of Lehmann & Joseph (2015).*

In this chapter, we review results from state estimates of biomass for Washington, Oregon, and California. Next, we review biomass supply assessments of the PNW, the western U.S., and the U.S. as a whole.

STATE ESTIMATES

Washington

Solid waste generally contains large quantities of organic materials (about 40%) that are easily decomposable (Figure 9.2; Ecology 2016). A large portion of the diverted organics are food and green waste (lawn and yard trimmings, leaves), and about 12% is woody biomass. The woody biomass includes such materials as trimmings from bushes and trees, clean lumber, pallets, crates, and trees from land clearing. These, combined with food and green organics, are the main sources of composted materials.

Solid waste in Washington has been sampled and characterized, most recently in 2015-2016 (Ecology 2016). The amount of clean wood (non-treated or painted, lumber, pallets, engineered, and natural wood) disposed was 193,375 tons, or 9.6% of waste disposed (Table 9.1).

Jensen & Moller (2018) used a broader general estimation method based on national data as another approach for estimating urban woody materials in the waste stream. They applied national data on waste generation based on population size; estimates were based on a detailed accounting for a particular county (Spokane County) and results extrapolated to the Washington State level (Table 9.2).

Jensen & Moller (2018) also estimated woody materials by using business types responsible for the most generation of woody materials by applying a common factor for material generation either on a per business or a per employee basis. Specifically, they estimated woody materials from land-clearing in Spokane County to be 180,000 tons per year, based on 180 landscaping services businesses with 892 employees (U.S. Census Bureau), and an estimate that tree trimming and landscaping companies generate about 1,000 tons per crew per business per year (Wiltsee 1998). This method may overlap with the yard debris categories in estimates of MSW disposed or recycled.

A 2008 estimate of potential biomass resources in Washington State estimated that forestry residues

Table 9.1. *Washington Waste Composition Study (statewide results collected over one year period, June 2015- May 2016; modified from Ecology 2016).*

Wood categories[1]	Percent	Tons
Yard & garden waste – pruning(s)	0.3%	6,389
Dimensional lumber	2.4%	48,955
Engineered wood	3.4%	68,778
Pallets & crates	3.0%	59,712
Other untreated wood	0.2%	3,873
Wood by-products	0.2%	4,563
Natural wood	0.1%	1,104
Total clean wood disposed	9.6%	193,375
WA statewide waste stream disposed	100%	2,007,171

[1] Defined in Ecology (2016)

Table 9.2. *Estimated total tons of woody fractions in Spokane County, Washington based on Moller (2009) study methods.*

Material type (woody fraction)	Spokane County, Estimated (tons/yr)[1]	WA State (tons/yr)[5]
Municipal Solid Waste (MSW)	22,829 - 38,048[2]	334,000 - 557,000
Land Clearing Debris	180,000[3]	1,800,000[6]
Construction and Demolition	44,185[4]	647,000
Total	247,014 - 262,233	2.8 M - 3.0 M

[1] Calculations based on 2015 Spokane County population data (Tweedy 2016)
[2] Based on 1.55 tons MSW per capita per year (Moller 2009), woody fraction is 3 to 5% of the MSW stream (Wiltsee 1998)
[3] Based on 0.12 dry tons of urban wood waste per person per year (Wiltsee 1998)
[4] Based on 0.09 tons per capita per year (Moller 2009), 2015 Spokane County population data (Tweedy 2016)
[5] Population proportioned to statewide based on per capita equivalent 14.6
[6] Assuming ten counties at Spokane County rate

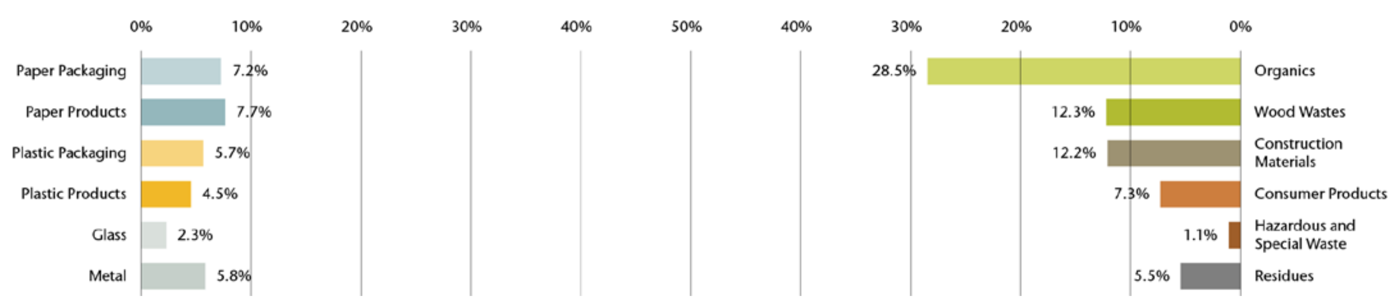

Figure 9.2. *Overall Washington statewide disposed waste stream composition by material class, 2015-2016. (Adapted from Ecology 2016)*

could provide 11.3 million dry tons per year of potential biomass, or 66% of the total estimated biomass available in the state (Frear 2008; Figure 9.3).

Washington State University researchers completed a Biomass Inventory and Bioenergy Assessment with support from the Washington State Department of Ecology. This study evaluated 42 types of waste across seven waste categories (field residue, animal waste, forestry, food packing, food processing, animal processing, and municipal organics) in each of the 39 counties in Washington (Ecology 2005; updated in Ecology 2011). Forest materials inventoried (logging residues, forest thinnings, mill residues, land clearing, and orchard debris) represented 5.8 million bone dry (BD) tons out of the total 10.6 million BD tons or 55% of inventoried biomass. These low-value biomass sources are typically composted, ground for hog fuel, burned onsite, or left in place. Forestry biomass totals and bioenergy potentials by county are shown in Figure 9.4.

The Washington Forest Biomass Supply Assessment estimated contributions of forest-based biomass as a byproduct of sustainable forest operations (Perez-Garcia et al. 2012, p.12). The model and data for available biomass presented in this report varies dramatically from estimates by other sources but is somewhat consistent with Cook & O'Laughlin's (2011) estimate of forest biomass supply for Washington at 1.2 and 1.6 million BD tons annually at $10 and $40 per BD ton, respectively. There are many qualifiers in this report that may explain low biomass assessments. For example, waste biomass left on harvested sites was estimated at 8 and 11 million BD tons per year in 2010 and 2015, respectively, apparently to reflect that much of the biomass is not yarded for recovery and use because it is too expensive to transport.

Washington's woody biomass from municipal wastes, forests, and agriculture was evaluated in a recently completed study by Amonette (2021). The work reviews the biomass supply Washington counties

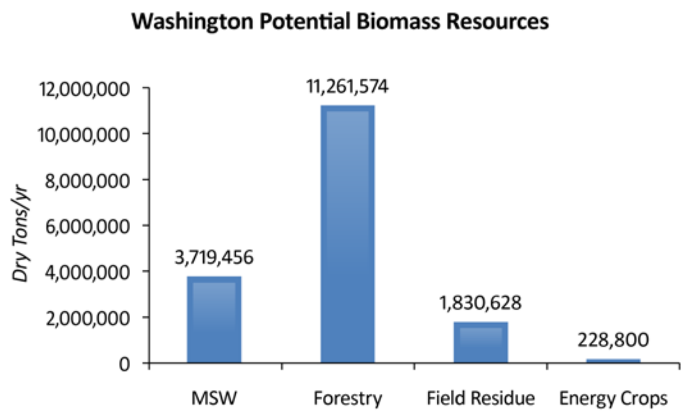

Figure 9.3. *Estimate of Washington's potential biomass resources. (Frear 2008)*

chosen for proximity of the wildland urban interface, fire risk, and the production of municipal solid waste, forest biomass, and agricultural crops. Amonette (2021) estimated available annual biomass totals of 8.7-25.4 green million metric tonnes (Table 9.3). The dominant biomass source is forestry residuals (aggressive & conservative harvest scenarios; approximately 73-91%, depending on scenario). The most promising opportunities exist where the wildland urban interface is in close proximity to agricultural land.

Biomass supply data can be combined with an assessment of the potential for soil carbon storage using biochar. Amonette (2021) focused on estimating the potential for atmospheric carbon drawdown by using biochar created from forestry residues and wood considered as "waste" that have historically been burned in slash piles because they have little economic value and includes spatial integration of soil productivity and crop information at 1 hectare resolution, separate accounting for changes (positive or negative) in soil organic carbon that results from feedstock harvesting and/or biochar application, and tracking biochar production and soil storage capacities over time. Washington's 100-year capacity for biochar production is estimated to be 140-380 million metric

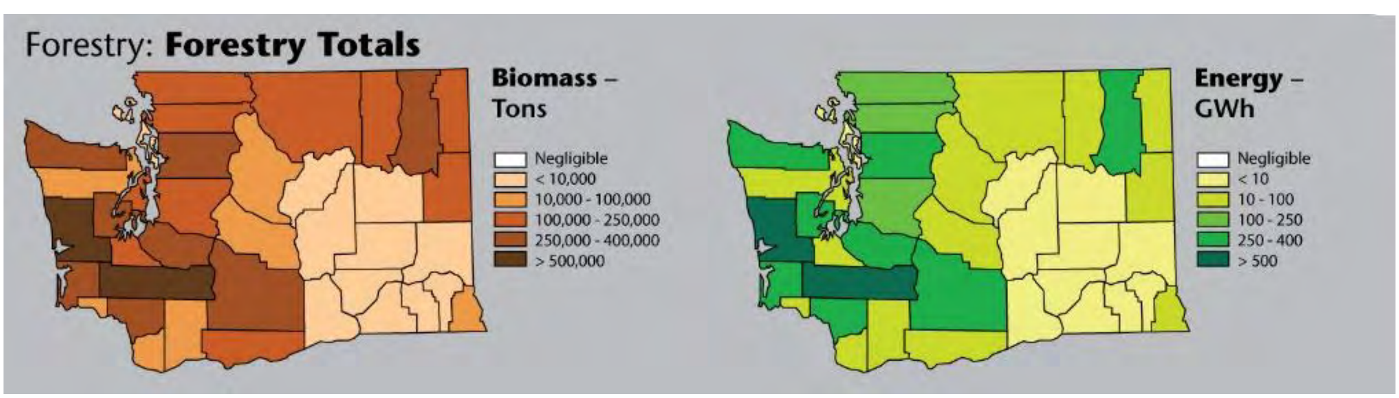

Figure 9.4. *Washington State annual forestry biomass totals and energy potential by county. (Ecology 2011)*

tonnes carbon, for eight scenarios including crop residue, MSW, and forestry residue feedstock streams. These would result in a 100-year climate offset of approximately 640-1,600 million metric tonnes carbon dioxide equivalent (CO_2e) and an ultimate drawdown of 38-93 parts per billion by volume of atmospheric CO_2e. At the maximum biomass-utilization rate, which is achieved after five decades, biochar production could offset between 9% and 20% of the greenhouse-gas emissions in Washington State (taken at 2018 levels). Under current storage potential assumptions, the biochar-carbon soil-storage capacity will be saturated in 62 to 106 years for the full scenarios that include crop residues, MSW, and timber-harvest biomass residues, however this limitation could be addressed through the development of additional storage reservoirs and technologies.

Table 9.3. *Annual biomass estimates for Washington State's 39 counties. (modified from Amonette 2021)*

Source	Biomass	
	1,000 green tons[1]	1,000 green tonnes[1]
MSW greenwaste[2]	47	43
MSW recovered wood[3]	343	311
MSW total	390	354
Harvested crop residues	2,230	2,020
Timber harvest scenario (conservative – landing only)	7,010	6,360
Timber harvest scenario (aggressive – landing and central facility)	25,300	23,000
Totals with conservative – landing only	**9,630**	**8,730**
Totals with aggressive – landing and central facility	**28,000**	**25,400**

[1] 50% moisture content is common for forestry biomass, but moisture levels can vary considerably. For example, wood that has been sitting in a slash pile for the summer can have much less moisture (18-25%).
[2] Greenwaste is defined as yard & garden waste—prunings from a survey conducted in 2015-2016 and reported on the basis of 2014 tonnage rates by the Washington State Department of Ecology.
[3] Recovered wood waste is dimensional lumber, engineered wood, pallets & crates, other untreated wood, and natural wood from a survey conducted in 2015-2016 and reported on the basis of 2014 tonnage rates by the Washington State Department of Ecology.

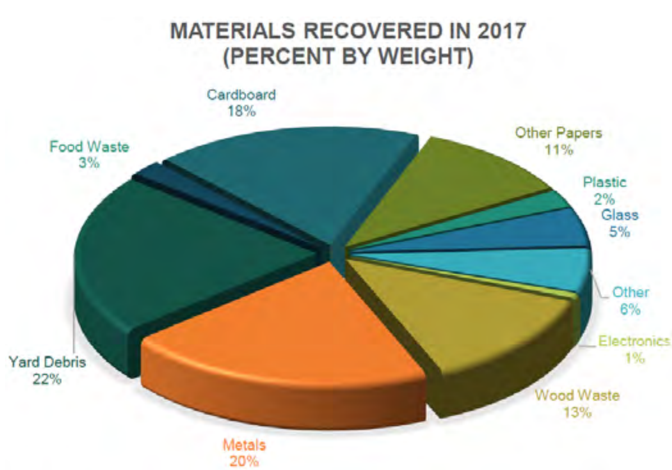

Figure 9.5. *Oregon material recovery in 2017. (ODEQ 2017)*

Oregon

In Oregon, the amount of clean wood biomass disposed in 2016 was 218,572 tons, representing 7.7% of waste disposed (Table 9.4; ODEQ 2016).

While no breakdown of the composition of compost feedstocks is possible in Oregon, the Oregon Department of Environmental Quality (ODEQ) produces a Materials Recovery report for recycled and recovered wastes (Figure 9.5). Nearly 300,000 tons of woody biomass are recovered from the waste stream annually for compost and energy use (Figure 9.6).

Table 9.4. *Oregon Waste Composition Study. (statewide results for 2016; modified from ODEQ 2016)*

Wood categories[1]	% of Total Waste	Clean Tons
Small prunings under 2 inches	0.40%	11,975
Large prunings over 2 inches	0.18%	5,627
Reusable lumber: unpainted	1.00%	30,742
Clean sawn lumber	2.85%	73,052
Clean engineered wood	1.53%	45,188
Cedar shakes and shingles	0.27%	6,925
Wood pallets and crates	1.47%	45,062
Total clean wood disposed	7.70%	218,572
OR statewide all sub-streams	**100%**	**3,060,520**

[1] Defined in ODEQ (2016)

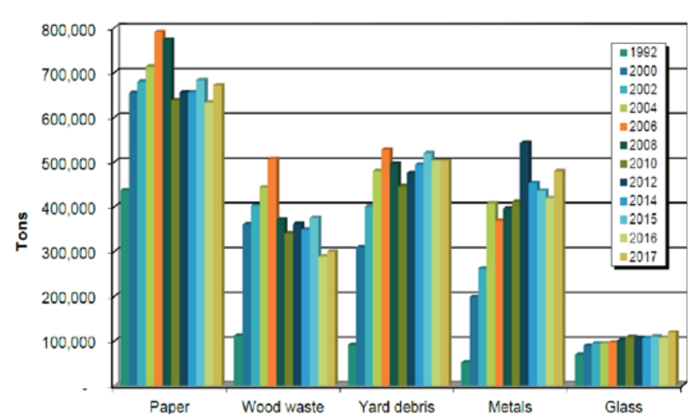

Figure 9.6. *Oregon wood and other materials recovered from waste stream 1992-2017. (ODEQ 2017)*

In a 2006 report for the Oregon Forest Resources Institute (OFRI), authors estimated potential biomass supply from fuel reduction treatments across 20 eastern and southern Oregon counties in the dry, inland forest region of Oregon (OFRI 2006). Key findings of this report were that 4.25 million acres (about 15% of Oregon's forestland) have the potential to provide forest biomass by thinning forest stands to reduce risk of uncharacteristic wildfire. Thinning these acres over 20 years could produce 1.0 million BD tons per year of woody biomass, not including merchantable sawtimber. It would cost an average of $59 per BD ton to deliver this biomass to processing facilities based on integrated harvesting and collecting which combines costs associated with biomass with the costs associated with merchantable timber. Costs for woody biomass would be much higher if only non-merchantable material is harvested.

California

In 2015, a group led by Katharine Mitchell (University of California Davis) used the Biomass Summarization Model (BioSum), a temporally dynamic, spatially explicit, forest stand development model, to estimate woody biomass for biofuel that could result from forest operations. In California, 7 million BD tons of woody residues would be available for the next 40 years (Mitchell et al. 2015).

In an assessment of biomass resources in California, Williams et al. (2015) found that although biomass in the state totals 78 million gross BD tons per year, biomass considered to be available on a sustainable basis is estimated to be 35 million BD tons per year. Of the gross resource, 25 million tons are from agriculture, 27 million from forest resources, and 26 million tons from municipal wastes, exclusive of waste in place in landfills and biomass in sewage. The current technical potential includes more than 12 million BD tons per year in agriculture, 14 million BD tons per year in forestry, and 9 million BD tons per year in municipal wastes.

REGIONAL AND NATIONAL BIOMASS SUPPLY ASSESSMENTS

In response to interest in creating renewable fuels, limiting fossil-based carbon emissions, reducing occurrences of catastrophic forest fires, improving forest health, and carbon sequestration, several organizations have conducted western regional biomass supply assessments focused largely on woody biomass from forests and including municipal and industry resources. The most relevant of these efforts are described below.

Forest Biomass Supply Analysis for Western States

In an assessment completed for the Western Governors' Association (Cook & O'Laughlin 2011), estimates were made of forest biomass at different roadside (forest material available on log landings near roads) price points. Forest biomass includes forest thinnings (small-diameter trees or brush removed to reduce hazardous fuels and/or improve forest health conditions), forest residues (logging slash), and mill residues. Washington and Oregon forest biomass supply ranges from 2.5 million dry tons at $10 per ton roadside price to 3.25 million dry tons at $40 per ton roadside price with roughly equivalent biomass contributed from each state (Table 9.5). In addition, five states have the greatest amounts of available forest biomass: California, Oregon, Washington, Montana, and Idaho. County-level tables for individual states are available separately.

Northwest Advanced Renewables Alliance

In 2016, the Northwest Advanced Renewables Alliance (NARA) project completed an assessment of available woody biomass created from timber harvesting, prescriptive forest thinnings, and mill residues that could be gathered and converted to jet fuel. The area for this assessment included Oregon, Washington, Idaho, and Montana. Logging residues averaged a total of about 14 million green tons annually for Oregon and Washington combined from 2002 through 2014, while residues in Idaho and Montana each averaged less than 2 million green tons annually (Figure 9.7; Berg et al. 2016, p. 21).

2005, 2011, and 2016 Billion Ton Reports

In 2005, Perlack et al. sought to answer the question: Could the U.S. produce a sustainable supply of biomass that could displace at least 30% of the nation's petroleum consumption? This study, which became known as the Billion Ton Report said 'yes'! However, the amount of potential biomass available was then revised to 137 million dry tons. If recent production increases from forest operations were considered, then the biomass potential could be 225 million dry tons. In 2011 an updated Billion Ton Report (USDOE 2011) noted that the potential forest biomass and wood waste available at $40 per dry ton would be about 79 million dry tons. This number is less than the 2005 estimate because of the change in pulpwood and sawlog markets.

Table 9.5. *Western states forest biomass supply availability in dry tons. (Cook & O'Laughlin 2011)*

State	Roadside price per ton						
	$10	$15	$20	$25	$30	$35	$40
AZ	75,829	145,672	170,010	222,846	230,036	231,423	231,601
CA	1,904,370	2,733,657	3,155,708	3,425,863	3,538,764	3,569,309	3,602,018
CO	100,120	123,366	197,806	228,948	274,847	300,161	312,104
ID	796,410	853,887	992,527	1,208,995	1,338,801	1,395,282	1,429,463
KS	8,720	8,720	8,720	8,720	8,720	8,720	8,720
MT	646,769	720,152	1,030,913	1,272,212	1,417,237	1,477,018	1,533,464
NE	4,971	4,971	4,971	4,971	4,971	4,971	4,971
NV	4,799	7,791	7,791	7,871	7,871	7,943	7,943
NM	78,314	90,450	143,710	213,109	279,713	292,336	301,716
ND	265	265	265	265	265	265	265
OR	1,339,728	1,466,478	1,541,285	1,585,410	1,611,490	1,618,589	1,648,377
SD	95,407	95,407	97,729	103,466	108,020	108,020	108,020
TX	3,022	3,022	3,022	3,022	3,022	3,022	3,022
UT	37,927	42,887	50,736	77,294	98,360	104,654	116,094
WA	1,152,105	1,274,302	1,360,558	1,467,007	1,517,302	1,550,350	1,606,562
WY	83,644	105,728	126,208	156,919	183,664	196,388	1,971,717
Total	**6,332,399**	**7,685,757**	**8,891,960**	**9,986,918**	**10,623,082**	**10,868,450**	**11,111,511**

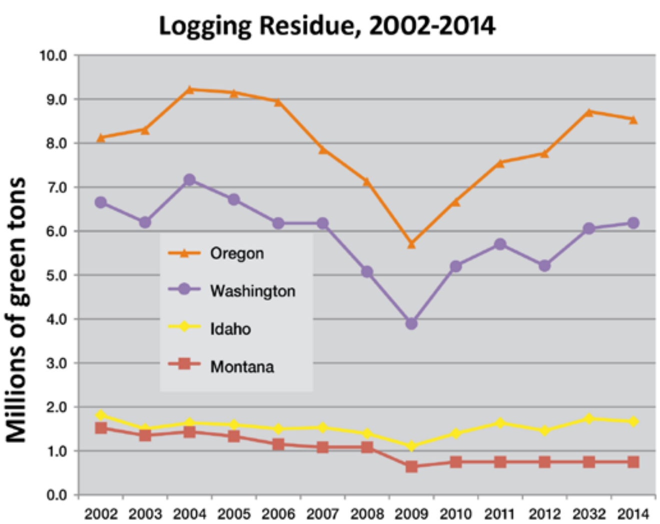

Figure 9.7. *Annual logging residue quantities from Idaho, Montana, Oregon, and Washington including bole wood, tops, and limbs 2002-2014. (Berg et al. 2016, p. 21)*

Table 9.6. *Estimated forest-based biomass supply from different sources.*

Integrated harvesting	Available material Billion Ton Report (MODT[1] in U.S.)[2]	Available material BRDI[2] (2008) report (MODT)	Available material (MODT in OR, WA, ID, CA)[3]
Logging residue	47	20	1-3
"Other" removal residues	17	6	1.8
Mill residues	n/a	15	6.8
Urban residues	47	3	n/a
Conventionally sourced wood (e.g., pulpwood)	74	4	1-6
Total	**185**	**48**	**100% of area treated**

[1] MODT = million oven dry tons
[2] Data from Skog & Stanturf 2011
[3] Data from Wear et al. 2013

According to the 2016 Billion Ton Report (USDOE 2016), in Washington, Oregon, California, Montana, and Idaho there is an estimated 8.3 million dry tons of logging residues available annually at $80 per dry ton. This estimate is expected to stay the same or increase slightly until 2050, particularly in Oregon and Washington. In all five western states with sizeable portions of logging residues it may be possible to collect logging residues at both conventional logging sites and, from thinning operations, thereby reducing fire hazard and insect and disease outbreaks.

Biomass Research and Development Initiative

An analysis commissioned by the U.S. Federal Biomass Research and Development Initiative (BRDI 2008) suggested that at $44 per oven dry ton[2] (ODT), about 48 million ODT of forest-based biomass would be available in the U.S. (Table 9.6). This analysis assumed that all forest-based and agricultural biomass would be available for biofuels. However, this material could be used for increased electric power, heat energy, or biochar production. This estimate from the BRDI report is lower than the Billion Ton Report estimate because it assumes that thinning operations would integrate harvest operations where sawlogs/pulpwood are harvested along with other biomass. Thinning operations are often limited by the demand for sawlogs and pulpwood in each region.

Additional Considerations for Forestry Biomass

It should be noted that gross biomass estimates do not account for the need for some amount of biomass to remain in forest and agricultural systems. For example, it has long been known that coarse and fine woody biomass, needles, and leaves are critical to ecosystem function and nutrient cycling, but that the amounts and turnover times vary by ecosystem. Therefore, only a portion of the residues would be used for biochar production and, where needed, a portion of the biochar would be added back to the forest soil to maintain or increase soil carbon.

Much of the low- and no-value woody biomass created from harvest operations are currently burned in slash piles or using broadcast burns. This practice wastes energy, creates smoke, and releases particulates into the air. Further, pile burning can produce an extreme heat pulse into the soil, which results in loss of soil organic matter, microbial population shifts, dead plant roots and seeds, and alteration of soil acidity, nitrogen, and physical properties. The scars left from pile burning often results in long-lived openings that have enhanced establishment of invasive or non-native plant species, but usually not native shrubs or trees (Rhoades & Fornwalt 2015).

CONCLUSIONS

Each of the inventory methods indicates that there is an abundance of woody biomass that can be sustainably harvested, converted to biochar, and applied on many different kinds of sites and soils. Conversion of woody biomass to biochar enhances the value of residues that are now considered "waste."

Key points are:

- Though municipal waste stream and agricultural residue resources are small relative to forestry residues, clean woody biomass in the solid waste stream is not well sorted and represent an opportunity to separate these resources for further conversion to biochar.
- Most woody biomass resources are from forest harvest operations. Different harvest, transport, and pricing scenarios affect the assessment of available biomass. For example, whole tree yarding and biomass collection on the landing would make gathering costs more reasonable than harvest operations that leave residues scattered across the harvest unit.
- Key limitations on forestry biomass collection depend on the specific analysis, but often include the cost of harvest, processing and transport, limitations on the amount of residue produced due to the need for coproduction of sawlogs or pulpwood, spatial distribution of biomass in relation to processing facility, and the need for and biological limits on forest health thinnings (Skog & Stanturf 2011).

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2 *Bone dry (BD) ton and oven dry ton (ODT) are both terms that imply biomass at 0% moisture, so are essentially interchangeable.*

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CHAPTER 10:

Biomass Handling

James Dooley, James G. Archuleta, Han-Sup Han, and Karen M. Hills

Biomass handling consists of gathering, comminution (reduction of particle size), and transportation. Biomass resources for biochar production include 1) urban woody biomass, 2) agricultural residues, and 3) woody biomass from land management operations. We briefly discuss the handling considerations with urban woody biomass and agricultural residues, then go into greater depth of handling of woody biomass from land management operations, which comprises the bulk of the available biomass resources in the Pacific Northwest (PNW).

BIOMASS TYPES

Urban Woody Biomass

Urban woody biomass generally consists of two categories: 1) materials collected through municipal green waste collection systems (yard waste, landscaping waste) and 2) construction and demolition debris (Dooley et al. 2018; Springer 2012). In both cases, existing collection systems are in place to gather the material for composting, landfilling, or production of bioenergy. In some cases, further sorting may be needed to exclude feedstocks that are problematic for biochar production (e.g., painted or treated wood). While some sort of sorting and/or comminution has already been performed (in the case of materials headed for other types of utilization), additional pre-processing of those materials may need to be implemented for the purpose of biochar production. The exact configuration of the comminution and transportation stages of handling will be quite dependent on the specifics of the biochar production system, particularly if it is co-located with a compost operation. (See *Chapter 7: Biochar Produced and Utilized at Municipal Compost Facilities*.)

Agricultural Residues

Agricultural residues can include wheat straw (Garcia-Perez 2012), hop vines, and orchard prunings (Ntalos & Grigoriou 2002; Pari et al. 2018). Comminution and transport will depend on the specific needs of the biochar production system and the properties of the biomass. Generally, biochar production systems using agricultural residues will be fairly small scale because of the widely distributed sources. For more background on costs associated with transport, drying and comminution of urban woody biomass and agricultural residues, see Lehmann & Joseph (2015, p. 821-826).

Woody Biomass from Land Management Operations

For the remainder of this section, we focus on woody biomass residues from land management operations, which comprise the bulk of biomass resources in the PNW. Many of the same considerations for handling methods may apply to other types of biomass resources as well.

Woody biomass that can be converted to biochar is a byproduct of a larger land management operation: landscape management, infrastructure (roads, pipelines, powerlines) vegetation management, wildfire protection, restoration treatments, or harvest of tree boles for use in forest products. The high concentration of biomass following these activities provides an opportunity to use these materials as biochar feedstocks (Figure 10.1). This woody biomass, consisting largely of brush, branches, tops, and thinnings, must be gathered from where it is cut, pre-processed to reduce size (i.e., comminution), and transported to a location where it is aggregated or to a site where it is converted to biochar. For simplicity, we refer to woody biomass from land management operations as 'forestry biomass' in this report.

Estimates of biomass feedstock availability in the PNW are provided in *Chapter 9: Biomass Supply*.

Figure 10.1. *Slash piles from timber harvest near Humboldt, California. Forest residues were piled for burning because they were not economically feasible to collect/process/deliver to a local biomass energy facility. (Photo: Han-Sup Han)*

BIOCHAR SYSTEM SCALE

The methods for accomplishing gathering, comminution, and transport of feedstocks look different for different types of biochar systems and are dependent upon the distance between the source of woody biomass and the biochar production site. The scale and logistics of biomass feedstock supply operations should be matched to the capacity and feedstock specifications of the biochar production system. Some general characteristics of the scales of biochar production discussed previously in this report are described below:

- **Place-based biochar production.** These are small (usually less than 500 tons per year biomass feedstocks), labor-intensive manual operations with short distance transportation of feedstocks (e.g., thinning or logging operations or on-farm production). Biochar production may use small low-tech units (e.g., flame-cap kilns) or managed piles. The defining feature of this scale of biochar production is that it can be replicated to cover large landscapes by adding additional crews and requires low capital investment in equipment. The biochar produced is generally used on-site, rather than being sold elsewhere.
- **Moderate-scale biochar production.** Moderate-scale biochar production converts biomass (usually 1,000-100,000 tons per year biomass feedstocks) into biochar. These systems involve transportation of biomass (less than 50 miles including unpaved forest roads) to a stationary biochar production site at or close to the location of biomass generation sites. Biochar production systems can be integrated into a combined heat and biochar system (CHAB) to provide heat to buildings (e.g., schools, hospitals) or can be part of a biomass utilization campus. Mobile systems such as air burners or gasification units can be used to produce biochar at or near the source of feedstock, which helps minimize transportation costs. At this scale, biochar production can be one of a suite of products such as heat, briquettes, electricity, bio-oil, and torrefied wood chips, which can either be used on-site or transported off-site for use elsewhere. Depending on the production system, there are two different levels of feedstock quality requirements for moderate-scale biochar production systems. Systems using gasification and pyrolysis often have specific requirements for feedstock size and moisture content. Air curtain burners do not require quality control of feedstock.
- **Large-scale, centralized biochar production.** Use of industrial biomass operations (usually greater than 100,000 tons per year biomass feedstocks) require high capital investment to build large facilities, purchase several machines, and maintain a large operations crew. Biomass transportation to a large-scale central biochar production facility assumes a one-way hauling distance less than 100 miles. Biochar is produced either as a main product or as a co-product of energy, food, or fiber (e.g., transport of biomass to an off-site boiler at a lumber mill, including handling, sizing, drying, and on-site power production).

Several factors affect the selection of an optimal scale of biochar production system, including amounts of woody biomass available, market demands, proximity to biochar markets, permit requirements, and the overall cost of operations. Place-based biochar is suited for local use at or near the biochar production site for small amounts (i.e., < 1 ton/day) of biomass, while a large-scale, centralized biochar production operations can most cost-effectively produce biochar in settings where there are industrial biomass operations, such as timber harvesting in industrial forestlands and fuel reduction thinning treatments in national forests, over a long period (>20 years). Biomass handling capacity and optimal operational logistics need to match up with the biomass production capacity. Moderate-scale biochar production utilizes opportunities to convert biomass into biochar near the source of biomass using mobile systems to minimize transportation costs. The Waste to Wisdom project (https://wastetowisdom.com/) illustrates an example of an integration of transportable biochar production system into landscape-level biomass handling logistics (Han 2018).

Further detail on harvest, preprocessing and transport of a variety of biomass feedstocks is provided in Garcia-Perez et al. (2012).

GATHERING

In general, a gathering step occurs whether or not biochar is the end goal for the woody biomass. Currently, it is typical for slash piles to be burned to dispose of residues. Biomass gathering at the small (place-based) scale is often done by a combination of human power and small tractors or loaders.

At the moderate and larger scales, woody biomass needs to be brought to the roadside and prepared for loading into vehicles for delivery to a centralized biochar production facility. Many commercial options exist for mechanized gathering of woody biomass at scales from small skid-steer machines with brush grapples to a team of excavators and forwarders gathering large amounts of forest residues (Figure 10.2). For a large capacity (>300 tons/day) biomass feedstock operation, it is important to note that biomass gathering productivity directly affects the subsequent comminution operation and should match the capacity of biomass comminution. Bisson et al. (2016) refers to this situation as "a balanced system" which helps minimize overall biomass handling cost.

Figure 10.2. *Gathering forest residues using a loader and a modified dump truck on a recent timber harvesting site near Humboldt, California. (Photo: Han-Sup Han)*

COMMINUTION

Woody biomass is often reduced in size (e.g., sawn to length, ground, or chipped) at the source to increase hauling payloads and enable bulk handling in regard to downstream conversion process and conversion equipment requirements (Figure 10.3). Key considerations for comminution include piece-size requirement (Table 10.1) and transportation (distance, loading/unloading, and bulk density). An additional consideration is moisture content. While dry materials are generally preferred for biochar conversion processes, chipping dry materials (<20% wet basis) may cause fire or excessive heat between knives and wood.

Table 10.1. *Piece size and content needs for various biochar production systems.*

Type	Scale	Maximum Diameter (inches)	Maximum Length (inches)
Pile	Intact branches and logs	6	42[1]
Flame-cap Kiln	Intact branches and logs	4	48
Mobile Carbonizer (e.g., Air Curtain Burner)	Intact branches and logs	12	120
Gasifier (1-5 tph)	Small chips, sawdust	1	1.5
Auger Pyrolysis	Small chips, sawdust	1	1
Combustion/Boiler, Stoker Grate	Chipped and/or ground	4	16
Combustion/Boiler, Fluidized Bed	Chipped and/or ground	1.5	3

[1] *U.S. Forest Service specification*

Figure 10.3. *A grinder (center) comminuting logging slash and directly loading ground materials onto a truck near Humboldt, California. (Photo: Han-Sup Han)*

Chipped and ground woody biomass is not compatible with biochar production units that require air flow between wood pieces like the flame-cap kiln or the large mobile air curtain burner systems. Those systems need intact branches and stems to allow increased amounts of air flow. Place-based biochar production often gravitates to flame-cap kilns which can use feedstock particle sizes of less than 4 feet in length to fit a 5-foot opening in the kiln (McAvoy & Dettenmaier 2020). Where the transport distance is greater than a few miles, some processing generally occurs to increase the bulk density of the biomass. The most common methods to prepare woody biomass for transport are to grind it with mobile horizontal grinders or to chip it with appropriately scaled mobile chippers.

Moderate-scale pyrolysis systems and gasifiers have been optimized by some manufacturers to accept screened chips and ground biomass, but large "firewood chunks" and sticks must be removed to avoid jamming of feeders. Large-scale systems that produce biochar as a co-product to steam and/or electricity are typically designed to use chipped and ground biomass from a wide range of sources discussed in this report.

Chipping and grinding operations can be scaled from a few tons per day to hundreds of tons per shift. At the small scale, and particularly in urban environments, orchards, and wildland-urban interface wildfire risk reduction sites, tow-behind chippers are directly coupled to small chip trucks. A hand crew gathers the biomass and feeds it into the throat of the chipper. Chips are blown into the truck. When the truck is full or the workday ends, the truck and crew drive to a dumping point. In this case the whole-plant chips would be dumped at a biochar production facility of any scale. A complication for this style of operation is that short blocks of roundwood do not feed into the chipper, so are tossed into the truck with the chips. This leads to a need for screening or other sorting at the biochar facility. The chunks would need to be further processed or diverted to a firewood market.

Large, tracked chippers and grinders of up to 1,000 horsepower can process 40 tons per hour of biomass provided a fleet of trucks and trailers are readily available to haul the material (Han et al. 2015; Bisson et al. 2016). If the comminuted raw biomass is piled on-site for decoupled hauling, transportation logistics could be simpler but the potential for contamination by rocks and debris becomes high. Such systems would require $4 - $6 million of capital for equipment, consume a thousand gallons of diesel per day, and require sophisticated logistics and operations management expertise. With a high level of year-round machine utilization, such systems are the best fit for delivery of woody biomass to centralized large-scale conversion facilities. However, the scale and continuity of biomass generating activities necessary for supporting such systems does not exist in many timber-dependent rural communities. Thus, there is also a need for cost-effective gathering and transport methods that are at an intermediate scale.

Another option (instead of chipping and grinding) is to crush materials using rollers into scrim (long strands) having a mean strand thickness of less than 0.24 inch. (Dooley et al. 2011; Du Sault 1984). The scrim may be cross-sheared to shorter, more flowable particles using a rotary shear machine. A screening system will redirect oversize materials to be re-crushed and recut, and fines, which contain high levels of soil, are stockpiled for use as mulch.

TRANSPORT

As previously mentioned, in the case of small-scale biochar production, gathering and transport operations are usually combined. As the transport distance increases, gathering becomes decoupled from transport (Figure 10.4). Transport of bulk, unprocessed woody biomass has a high cost per unit distance due to low bulk density (typically 3-5 lb per cu.ft.). If the transport distance is less than 5-6 miles, an option using hook-lift containers or high-cube dump trailers can be cost-effective (Montgomery et al. 2016). Transportation cost can represent more than 50% of the total biomass handling cost in many cases, especially with situations involving long hauling distance (>50 miles one-way) and poor quality of forest roads (Pan et al. 2008). Furthermore, transportation logistics and scheduling should be well-coordinated with comminution and biochar production operations.

Figure 10.4. *A chip van transporting biomass feedstock from a comminution site in the woods near Humboldt, California to a biochar production facility. (Photo: Han-Sup Han)*

Though chipping and grinding commonly occur prior to transport, other strategies for increasing bulk density have been used. In some areas baling into round or large rectangular bales greatly increases the transport density, and thus can reduce cost of hauling with conventional flatbed trucks (Dooley et al. 2018). Baling reduces storage costs and preserves piece size for milling at the destination (Figure 10.5). Bales of densified biomass or windrows and piles of gathered loose biomass are staged for loading onto trucks or for further processing into a bulk flowable format such as grindings and chips. Recently, an innovative large-scale hauling scheme was developed in Washington State that combines transport of bulk unprocessed forest residues in end-dump trailers with a heavy payload of merchantable logs on top. The logs compress the biomass to double its bulk density and provide a high-revenue product in the load (Barrier West 2018).

Figure 10.5. *Wildfire protection thinnings were used to produce 4mm feedstock for biochar production. In this example, biomass was transported intact for comminution and screening at a centralized facility. (Photo: Forest Concepts)*

OTHER CONSIDERATIONS FOR BIOMASS HANDLING

Moisture is a consideration because it affects the time for producing biochar and the energy balance of conversion systems. A moisture level less than 20% is best for optimal use of most technologies, but the specifications vary (Belart et al. 2017; Stokes et al. 1993). With some types of units, excess heat is used to dry feedstock. For example, a mobile gasification unit converting wood chips into biochar requires a feedstock moisture content of less than 25% (wet basis) for an optimal operation (Eggink et al. 2018). Air curtain burners can handle wet biomass (>50% moisture content) after initial start, but dry materials still offer increased production of biochar at a given time.

Since feedstocks account for a large portion of the cost and labor for biochar production (even when the cost is simply gathering and loading), taking a systems approach to all gathering, comminution, transport, and handling is paramount. There is an opportunity to more optimally match at-source (in-woods) feedstock preparation with the biochar production system chosen for any particular project or biochar enterprise (Paulson et al. 2019). In an analysis of system logistics for a biomass recovery operation, Bisson et al. (2016) found that to control costs, it is necessary to maximize comminution, so that capacity of processing stage dictates upstream and downstream activities.

High quality feedstock can be produced by separating stem wood from other residues during timber harvest operations (Bisson & Han 2016; Kizah & Han 2016). Tree tops and small-diameter trees can be delimbed and piled in separate from slash piles for lowering moisture content and efficient transportation. Sorting of feedstocks may make feasible the use of a chipper (rather than a grinder), which would be better for meeting the particle size specifications for some biochar production technologies (Bisson & Han 2016).

Biochar production can be integrated into the existing forest products manufacturing operations to enhance an economically sustainable operation (e.g., lumber pellet, post/pole, firewood). Operations using woody residues such as slabs, chunks, and sawdust as a product feedstock and an energy source, have the opportunity to adapt to add production of biochar. Additional amounts of biomass feedstock can be sourced directly from timber harvesting sites to increase production of biochar and improve utilization of small-diameter trees and forest residues.

For example, recently Integrated Biomass Resources (IBR) a plant in Wallowa, Oregon adapted the plant's boiler to add biochar to the normal power production for the boiler with a grant managed by Wallowa Resources. This system takes advantage of mill residues in the production of post/poles and kiln dried firewood, to capture a new product. By finding similar opportunities, biochar manufacturing can utilize existing transport systems, and thermal conversion (boilers) to take advantage of existing efficiencies.

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CHAPTER 11:

Biochar Production

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BASICS OF BIOCHAR PRODUCTION & CO-PRODUCTS

In production of biochar, thermochemical processes that can be used to treat biomass include pyrolysis, gasification, hydrothermal processing, and combustion. Each of these processes is defined by specific operating conditions (e.g., temperature, presence of oxygen) and feedstock requirements for optimal conversion to the product of primary interest. Each process results in varying fractions of gaseous, liquid, and solid products.

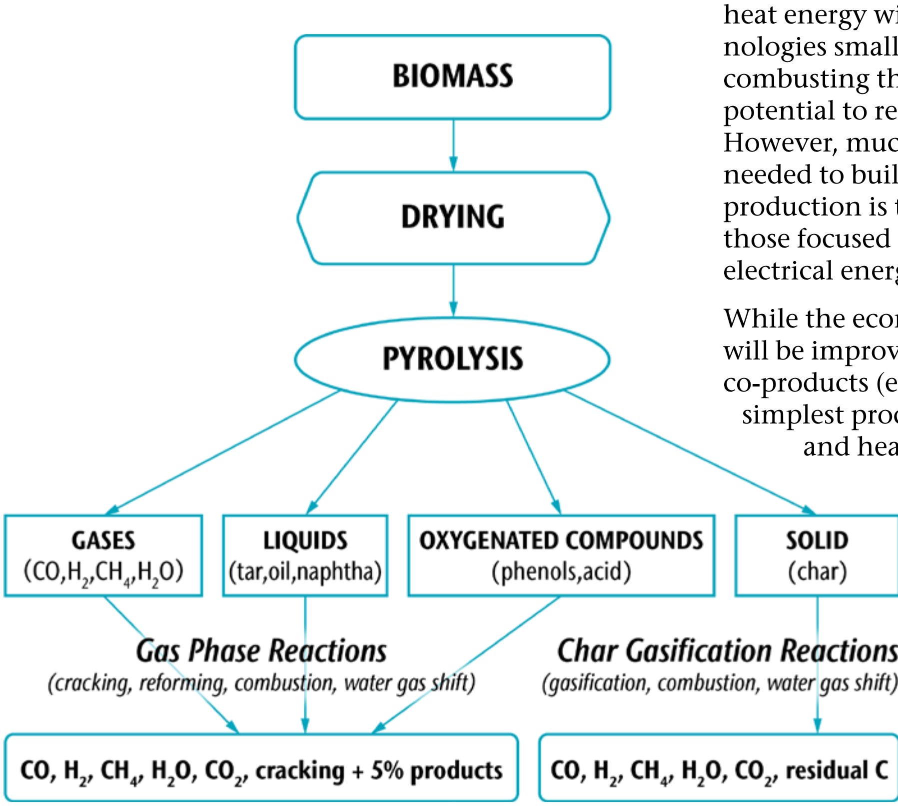

Figure 11.1. *Gasification routes. (Source: Sikarwar et al. 2016, licensed under CC BY-NC 3.0)*

Though other publications have emphasized the gaseous bio-energy products of such processes (e.g., bio-oil, synthesis gas or "syngas") with biochar as a co-product, in this discussion, we focus primarily on biochar as the main product, with heat and electrical energy as co-products of secondary interest. The reasons for this are as follows: when producing biochar, heat is the simplest form of energy to capture and utilize, electrical energy can be generated from heat energy with a wide range of available technologies small and large; rather than immediately combusting the gases released from biomass, there is potential to refine the gases into bio-oil and syngas. However, much larger investments of capital are needed to build facilities for which gaseous fuel production is the primary goal, as compared to those focused on biochar production with heat and electrical energy co-products.

While the economic viability of biochar production will be improved by production of high-value co-products (e.g., wood acids for use in pesticides), the simplest production scheme is one in which biochar and heat are the primary products. Here we aim to provide a broader overview of thermochemical processes and technologies most relevant to biochar production in its current state of commercialization.

All biochar is a result of pyrolysis (the reaction) but not all biochar is made with a dedicated pyrolysis reactor (the technology type). Further, all biochar is the result of

Table 11.1. *General conditions of pyrolysis (slow and fast), gasification, and combustion.*

	Slow Pyrolysis	Fast Pyrolysis	Gasification	Combustion
Time required for reaction	minutes - hours	seconds	seconds	seconds
Typical particle size for operation	wood chips - logs	saw dust - milled wood	milled wood – wood chips	wood chips
Temperature (°C)	300-800	400-700	750-1,000	1,000-1,200
Main product	biochar	bio-oil	syngas	heat
Biochar yield (wt. %)	35-50	15-30	5-10	<2

a lack of complete combustion (the reaction), even biochar produced in a combustion or gasification reactor (the technology type). This is an important distinction to acknowledge in the following sections in which we discuss both thermochemical conversion reactions and technology types.

THERMOCHEMICAL CONVERSION OF BIOMASS TO BIOCHAR

The progression from biomass to the resulting products is shown in Figure 11.1. Biomass moves from drying to pyrolysis, which is a thermal decomposition process in the absence of oxygen that separates components of biomass into gases, liquids, oxygenated compounds (e.g., wood vinegar), and solid (biochar). Biochar recovery occurs at this stage. Some systems capture the gases, liquids, and oxygenated compounds for making other products, while in other systems these products undergo gasification (further thermochemical conversion in the presence of oxygen).

While there are a number of thermochemical conversions that can result in biochar, here we focus on pyrolysis (slow and fast), gasification, and combustion. Torrefaction, hydrothermal carbonization, and hydrothermal liquefaction are other chemical conversion processes that have arisen from a bioenergy approach and are discussed in further detail by Brown (2019) and Clifford (2020).

Pyrolysis

Depending on the particle heat transfer rate achieved, it is possible to identify two types of pyrolysis reactors: *slow and fast pyrolysis*. Table 11.1 shows a comparison of these two processes with gasification and combustion, while Figure 11.2 offers a comparison of the distribution of resulting products.

Slow Pyrolysis

Slow pyrolysis, also called conventional carbonization, produces biochar by heating biomass at a low heating rate (around 5-7 °C per minute) for a relatively long residence time and typically uses large particles like wood chips or even whole logs. These conditions produce less liquid (30-50 by weight [wt. %]) and more biochar (35-50 wt. %) than fast pyrolysis.

Fast Pyrolysis

With fast pyrolysis, the process of heating biomass is rapid (heating rates of over 300 °C/min). Fast pyrolysis is typically used to obtain high yields of single-phase bio-oil. Fast pyrolysis uses small particles, generally smaller than 5 mm in diameter, due to the low thermal conductivity of lignocellulosic materials. High-rate heating of lignocellulosic materials typically yields 60-75% bio-oil, 15-30% biochar, and 10-20% non-condensable gas, and can be done in seconds. Most fast pyrolysis systems currently in commercial use consume the biochar that they make rather than recovering the biochar.

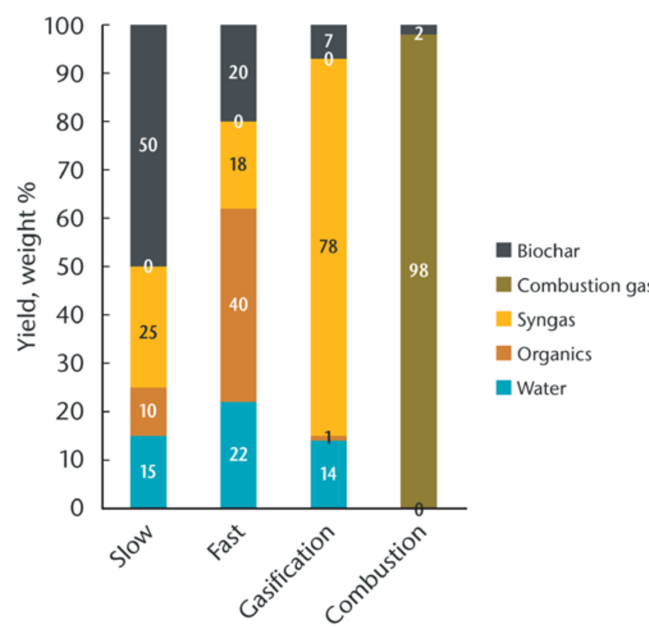

Figure 11.2. *Typical distribution of products from the three main thermochemical conversion technologies used to process low-moisture biomass feedstocks: slow pyrolysis, fast pyrolysis, and gasification. (Modified from Zhu et al. 2018)*

Gasification

Biochar can also be produced by gasification, a process that differs from pyrolysis in that some oxygen is present and much higher temperatures are used (>750 °C; Table 11.1). Gasification has been used since the 1800s in energy generation from coal and biomass. Gasification is used to convert carbon-based materials into carbon monoxide, hydrogen, and carbon dioxide (syngas or producer gas). The gas mixture can then be combusted to generate power. While gasification technologies were designed for power, rather than biochar production, biochar can be produced with this approach.

An appeal of this technology group is that there are readily available gasification units. A drawback of this technology group is that the conversion efficiency of biomass to biochar appears to be limited to relatively low levels, though conversion efficiency depends on the specific technology used. More information on gasification technologies can be found at the *Biofuels Academy website*.

Combustion

Reactors relying on combustion are primarily designed for generating heat, which is commonly used for a combination of steam turbine electrical generation and secondary heat uses such as curing lumber or drying grain. Biomass is heated in the presence of oxygen and the resulting gases are burned in the same vicinity of the biomass, thus driving the continuation of the process.

Though the word combustion seems antithetical to the production of biochar, combustion as a technology type is perhaps responsible for a majority of the biochar produced in North America. The key is that not all combustion technologies result in 100% complete combustion (which would yield ash as the solid product); in fact, the opposite statement is more accurate as combustion technologies typically do not result in complete combustion. When oxygen is present, but insufficient for complete combustion, biochar can be pulled out of the system. Combustion in a boiler will generally yield 1.5-2% biochar.

TECHNOLOGIES

Technology Considerations

Technologies for biochar production can be distinguished by mode of operation, need for pretreatment of feedstock, heating considerations, and emissions. In some cases, post-processing is used to further modify the characteristics of the resulting biochar.

Mobility

One of the most defining features of technologies is whether they are designed to be relocatable or operated at a fixed location. Relocatable technologies are generally small-moderate scale and can be operated at forest landings, lowering cost of feedstock transport.

Mode of Operation

Depending on the mode of operation, technologies can be classified as batch, semi-batch, or continuous.

Pretreatment of Feedstock

Pretreatment of feedstock improves the efficiency of pyrolysis and can include drying, size reduction (generally with a knife chipper or hammer mill; See *Chapter 10: Biomass Handling*). In general, slow pyrolysis for production of biochar and heat does not require as much pretreatment as fast pyrolysis for bio-oil production. Homogeneity in feedstock (in size and geometry) minimizes variations in dryness and off gassing of volatile organic compounds (VOCs) due to a set detention time in continuous modes of operation,

Heating

Biochar production requires heating the biomass to temperatures in which the biomass denatures moisture and volatile compounds, and the biomass is modified to amorphous and crystalline structures. In general, this is done with a flame heating the biomass, either directly or indirectly, to temperatures in excess of 400 °C. In order to create the lowest emissions profile, the biochar production equipment should be designed to operate on the synthesis gases produced for the process heat to pyrolyze or gasify the biomass. Oxygen contacting the biomass can burn off excessive carbon, but this is often a fair trade-off due to the potential for process intensification. Utilizing heat produced during biochar production can be used for drying incoming biomass which can improve overall efficiency. (See Combined Heat and Biochar, page 154.)

Emissions

Off-gas from the pyrolysis or gasification process (also referred to as syngas or producer gas) has high energy content, typically rich in mixtures of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen gas (H_2), water (H_2O) and volatile and semi-volatile hydrocarbons including methane (CH_4). Combustion of the syngas can provide more than enough heat to drive the pyrolysis process, if designed into the overall process. Syngas can provide more than the amount of energy needed for drying and thermal treatment. However, a supplemental gas may be required for startup and shutdown at a minimum. Any biochar technologies need to comply with relevant regulations on emissions. Emissions issues are discussed in *Chapter 12: Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems*.

Postprocessing Technologies

Postprocessing of biochar can include a number of processes that may take place after pyrolysis including steam quench systems are applied that may include processes to further activate, or functionalize, the biochar, or physical modifications such as size reduction or pelletizing for ease of handling, blending, or application. Biochar materials can be engineered for a particular end-uses, by methods such as adding particular minerals, acids, plant nutrients, or activation with carbon dioxide to alter functional properties. Further information on engineered biochar for particular environmental services can be found in Garcia-Perez et al. (2017).

Technology Types

This section discusses some of the most commonly used types of technology for production of biochar. An in-depth understanding of the socioeconomic context of biochar production must govern specific choices of technologies. Production units should be chosen with specific context (e.g., feedstock types and amounts, products) and a clear business model in mind. Slow and fast pyrolysis reactors have been reviewed elsewhere (Garcia-Nunez et al. 2017). Specific technologies used for producing biochar at or near the forest (rather than at centralized facilities) are described further in Page-Dumroese et al. (2017). Table 11.2 provides an overview of most applicable technology types for biochar production, with text descriptions for each provided below. Table 11.3 shows further considerations in terms of categories of biochar production equipment and contexts in which each best fits.

Flame-Cap Kiln

The flame-cap kiln (or mini kiln) is a small, low-cost kiln operated by small landowners with the primary benefit of being able to be transported by one to two people. Forest residues are generally cured for a year or more prior to putting in the flame-cap kiln. Flame-cap kilns are an example of a batch system and have low rates of biochar production. Batch systems require to be lit, filled to capacity, cooled/quenched/emptied and repeat. This operation can be slower than desired, depending on biomass to be consumed and need to move on to additional treatments. This can be overcome by increasing the number of production units, but not without proportionally increasing labor logistics and costs to archive higher production rates. Therefore, flame-cap kiln production tends to remain low (McAvoy & Dettenmaier 2020). Larger flame-cap kilns (e.g., “big box” kilns) exist with larger openings that may be filled by a loader rather than by hand. For more information on types of flame-cap kilns, see Table 4.1 in *Chapter 4: Place-Based Biochar Production*.

Conservation Burn

An alternate method of constructing slash piles exists in which base logs elevate the rest of the pile above the soil and these limit soil impacts and can result in approximately 10-15% of the biomass retained as biochar (depending on pile conditions). Piles need to be quenched or built so they self-extinguish, but biochar can be made which is suitable for soil restoration in or near the piles. More information on techniques for using conservation burns to produce biochar is available in Page-Dumroese et al. (2017).

Mobile Carbonizer

The key feature of these systems is their mobility. One example of a mobile carbonizer is an air curtain burner operated in “pyrolysis mode.” This technology was created as an alternative to slash pile burning (with a more favorable emissions profile) and disposal rates are typically 1-10 tons per hour. Large trees and brush can be loaded into the air curtain burner without chipping and there are relatively few moving parts. When operated in standard mode, ash results rather than biochar. However, by changing some of the operating parameters, these units can be used to produce biochar (AirBurners n.d.).

This type of modified air curtain burner has higher production capacity than the previously mentioned batch systems. They are considered “throughput systems” because biomass is introduced at one end, heated to reduce material to charcoal. Once charcoal forms on the burning biomass it is separated from the burn box and quenched at the other end. This type of production is intended to eliminate part of the batch system to increase biochar production. At least two equipment manufacturers are in the market (TigerCat & AirBurners Inc.).

Table 11.2. *Biochar production processes (Modified from Miles & Wilson 2020)*

Equipment	Processes[1]	Typical Capacity Input of Feedstock[2,3]	Typical Capacity Output of Biochar[2,3]	Status[4]	Examples
Flame-Cap Kilns	G, C	0.6 tpd/kiln × 180 days = 110 tpy/kiln[5]	2 CY/kiln/day × 180 days/yr = 360 CY/kiln/yr[5]	I	Ring of Fire, Oregon, WarmHeart, Big Box, Kon Tiki
Conservation Burn	G, C	variable[6]	Estimated 10-15% of pile volume[7]	I	Sonoma Ecology Center, Wilson Biochar Associates
Mobile Carbonizers	G, C	70 tpd × 180 days = 13,000 tpy	22 CY/day × 180 days/yr = 4,000 CY/yr	I	AirBurner, Tigercat
Combined Heat and Biochar	C, G, P	4 tpd × 310 days = 1,200 tpy	10 CY/day × 310 days/yr 3,100 CY/yr	I, Es	BET, Biomacon, Pyrocal, ICMICM
Portable Retorts	P	1.3 tpd/retort × 155 days = 200 tpy/retort[8]	4.6 CY/day/retort × 155 days = 710 CY/retort/yr[8]	I	Biochar Now
Boilers/Combustion	C	10 tpd × 310 days = 3100 tpy[9]	70 CY/day × 310 days = 22,000 CY/yr[9]	I, Es	Oregon Biochar Solutions, Pacific Biochar
Rotary Kilns	P	240 tpd × 310 days = 74,000 tpy	750 CY/day × 310 days = 230,000 CY/yr	Es	National Carbon Char Technologies, Heyl & Patterson, FEECO, Schenck Process, Sanju Environmental
Heated Augers	P	6 tpd × 310 days = 1,900 tpy	100 CY/day × 310 days = 31,000 CY/yr	Es, I	Pyreg, Artichar, VOW/Biogreen, Carbon Powdered Mineral Technology
Gasifiers	G	20 tpd × 310 days = 6,200 tpy	38 CY/day × 310 days = 12,000 CY/yr	Em, I, Es	V-Grid, KDS Systems, ICM, Ag Energy Solutions, Pyrocal, Coaltec

[1] Processes: C – Combustion, G – Gasification, P – Pyrolysis
[2] Capacity: Mobile 180 days/yr, 1,800 hrs/yr; Stationary 310 days/year, 7,440 hours/year; 200 lb dry/CY
[3] Abbreviations: CY (cubic yards), tpd (tons per day), tph (tons per hour), tpy (tons per year)
[4] Status: Em – Embryonic (bench, pilot), I – Innovative (limited adoption), Es – Established (widespread)
[5] As many as 8 flame-cap kilns can be operated by a work crew at a single site.
[6] Conservation (slash pile) burns vary widely in size, depending on whether material is gathered by hand or machine.
[7] Dumroese et al. 2017
[8] Each retort cycle requires 48 hours. Typically deployed in groups of 40 for maximum economic throughput, or 3 per trailer for short-term sites.
[9] Bioenergy facilities; assumes 2% of total biomass feedstock is added to maintain constant power output during biochar production; fraction of total biomass feedstock that converts to recoverable biochar is unknown but is significantly larger than that needed to maintain power.

Table 11.3. *Biochar equipment type considerations.*

Equipment Type	Scale[1]	Production Capacity per Unit (tons/day)[2]	# Units in Parallel	Feedstock Processing Requirement	Feedstock Transport. Distance (miles)	Integrations	Heat	Electricity	Capital Cost	Labor Needs
Flame-Cap Kiln	Place-based	0.1-1.0	8-12	cut to length	0	forest application			very low	high
AirBurner	Place-based, Moderate	0.3-7.0	1-4	cut to length, bale or chunk	0-10	forest application /biochar revenue stream			low	medium
Mobile Pyrolysis Unit	Moderate	0.3-9.0	1-40	chip, bale or chunk	0-10	biochar revenue stream			medium	medium
Industrially Integrated Unit[3]	Moderate	0.3-75.0	1-2	chip	0 (feedstock on-site for other process)	use in compost or other mfg. process on site	●		medium	medium
Combined Heat and Biochar	Moderate	0.1-1.0	1-2	chip	up to 50	biochar revenue stream	●		low to medium	low
Central Boiler	Large	5.0-10.0	1	chip	up to 50	biochar revenue stream	●	●	high	medium

[1] Descriptions of place-based, moderate, and large-scale centralized production are provided in *Chapter 1: Introduction*.
[2] Values are for biochar produced.
[3] Industrially integrated units can include gasifiers, rotary kilns, heated augers, and boilers from Table 11.2.

Combined Heat and Biochar

In the process of making biochar, thermal energy is produced which can be used for heating or cooling. Combined heat and biochar (CHAB) can be used to provide heat for a variety of purposes, for example. vermicomposting, or for heating greenhouses, for product drying, or for water heating. Capturing this heat and putting it to use improve the economic viability of the biochar operation and improve climate impacts. For more information, including a review of six systems available on the market and appropriate for CHAB, see Wilson & Miles (2020).

Portable Retorts

Historically, the term retort referred to a reactor that has the ability to pyrolyze pile-wood, or wood logs over 30 cm long and over 18 cm in diameter (Emrich 1985). In modern times it refers to a pyrolysis system (partially closed vessel of biomass heated from exterior), in which the gases released from the vessel are captured and used to provide heat for driving the reaction in the closed vessel. Some examples of portable retort types include Adam retort and screw-auger retort.

Boiler/Combustion

Conventional biomass boilers can be converted by reducing the residence time of biomass in the boiler, resulting in greater production of biochar, with a reduction in energy production. Alteration of existing boilers for producing biochar may require changes to feedstock moisture content and particle size, oxygen ratio for optimal biochar production. This type of retrofitting of boilers has occurred on a limited scale in the region and, in some cases, may be more economical than competing options. A description of modification options is offered in *Chapter 6: Centralized Biochar Production Facilities*.

Rotary Kiln

Rotary kilns were developed for large-scale forest harvest operations and can process up to 20 tons of feedstock in 24 hours. A rotating metal tube allows the feedstock (wood chips) to be rapidly heated with gas burners to 400-600 °C. The rotary kiln offers a great amount of control to the operator and is housed within a shipping container. The main product can be bio-oil or biochar, depending on the process conditions.

Heated Augers

The heated auger reactor is usually fed at one end through a hopper or a feeding screw, which carries the biomass to the hot zone of the reactor where it is carbonized. The gases and vapors are extracted and sent to a condenser (Garcia Nunez et al. 2017). Studies with woody biomass show biochar yields between 17 and 30 wt. % and yields of oil between 48 and 62 wt. % (Meier et al. 2013).

Gasifiers

Gasifiers can be either updraft (fuel enters from the top, gasifying agent from the bottom) or downdraft (both fuel and gasification agent enter from the top). Downdraft gasifiers (SERI 1988) can produce fuel that you can run in an engine and result in biochar yields of 2-5%. Updraft gasifiers (e.g., the Lurgi reactor) operate more like a furnace with biochar yields of up to 15%. While traditional updraft gasifiers are designed to burn the wood all the way to ash, they can be designed to output biochar as well.

Further reading on gasification can be found in Sikarwar et al. (2016).

This section does not contain a comprehensive list of all thermochemical conversion technologies, but instead focuses on systems that have high technology readiness levels. For further reading on the practicalities of biochar production, see Lehmann & Joseph (2015; Chapters 3 and 4).

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CHAPTER 12:

Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems

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Biochar production systems (BPS) need to comply with all applicable regulatory requirements, which depend on the size and location of the facility, characteristics of technical operation, feedstock composition, origin, and designation, site land use zoning, regulating jurisdiction, and nearby environmental conditions. Sites may require permits for air, storm water, waste discharge, solid waste, and conditional use as well as other environmental review. Stakeholders in the Western U.S. coastal states (California, Oregon, and Washington) have identified air emissions as a major barrier to more widespread adoption of biochar production. Thus, this section provides an overview of some of the common issues relating to biochar air pollutant emissions and air emissions permitting for BPS, relying on the regulatory experience of a range of experts.

States and tribal agencies have primacy for implementing the U.S. Clean Air Act, which provides a federal basis for air quality permitting.[1] In some states, local air agencies have been established over smaller areas. Different tribal, state, and local entities have different approaches to permitting biochar units because of variability in multiple and emerging technologies, local differences in air quality issues, differences in state regulations, and other factors.

EMISSIONS FROM BIOCHAR PRODUCTION SYSTEMS

Air pollutant emissions from biochar production units vary widely depending on biomass feedstock composition and BPS design, operation, and use of add-on control devices. However, generally speaking, the following potential air pollutants should be considered:

Criteria Air Pollutants

Criteria air pollutants are air pollutants for which the U.S. Environmental Protection Agency (EPA) has established National Ambient Air Quality Standards (NAAQS) and include particulate matter (PM), ozone, (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and lead (Pb). Volatile organic compounds (VOCs), carbon containing compounds involved in ozone formation, are also regulated. Biomass feedstocks typically have very low sulfur and Pb levels, so SO_2 and Pb emissions tend to be less of a concern, but other criteria pollutants can be produced during biomass processing. Emissions of some criteria pollutants can be reduced with process controls or add-on technologies.

The EPA has established NAAQS for $PM_{2.5}$, fine particulate matter with an aerodynamic diameter less than 2.5 micrometers, and PM_{10}, particulate matter with an aerodynamic diameter less than 10 micrometers. $PM_{2.5}$ settles in the deep and sensitive parts of the lungs and aggravates respiratory illnesses including emphysema, asthma, and bronchitis. Particulate matter, especially $PM_{2.5}$ in the form of smoke, soot, and ash, results from inefficient combustion of BPS pyrolysis or gasification off-gases and the inorganic, non-combustible constituents of the biomass feedstock. PM emissions are controlled by ensuring complete combustion of the off-gasses (often called "syngas" or "producer gas"), and through the use of add-on controls such as cyclones, baghouse filters, electrostatic precipitators, or wet scrubbers that remove entrained particulate matter from the exhaust gases.

Tropospheric (ground level) ozone is not emitted directly into the air, but is created by chemical reactions between VOC and NOx in the presence of

1 *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.*

sunlight. Tropospheric ozone, appearing as smog or haze, is a strong irritant that damages the respiratory system. Some VOCs are also regarded as toxic air pollutants by the U.S. EPA because of known health impacts. VOCs are emitted during the pyrolysis and gasification processes, and can be controlled by ensuring complete combustion. Nitrogen oxides (NOx), including NO_2, are emitted from high temperature reactions between nitrogen contained in the biomass fuel (fuel NOx) or in the combustion air (thermal NOx) with oxygen in the air. NOx emissions can be controlled through the use of fuel and air mixing, and add-on controls involving catalytic and non-catalytic reduction reactions.

Carbon monoxide (CO) is a relatively unreactive compound, but the gas is poisonous to humans and other air-breathing creatures that need oxygen. It also indirectly contributes to the buildup of some greenhouse gases in the troposphere. CO is generated during the pyrolysis and gasification process and from the incomplete combustion of biomass syngas. It is controlled through ensuring complete combustion.

Emissions of criteria pollutants vary widely between systems, and datasets are not extensive. However, it is clear that biochar production units can have considerably lower emissions of PM, CO, VOC, and NOx than open pile burning or burning during wildland fires (Clerico & Villegas 2017; Cornelissen et al. 2016; EMC 2017; Miller & Lemieux 2007; Springsteen et al. 2015; Springsteen et al. 2011). Table 12.1 compares criteria air pollutant emissions from open pile burning with a number of different biomass conversion technologies.

Toxic Air Pollutants

Toxic air pollutants, also called hazardous air pollutants (HAP), are pollutants that cause or may cause cancer, reproductive effects, birth defects or other serious health effects, or adverse environmental and ecological effects. Section 112 of the Clean Air Act identifies 187 hazardous air pollutants. Individual state regulations can identify more. Emissions of toxic air pollutants can vary significantly depending on biomass constituents and conversion unit design and operation – but could potentially include metals, volatile and semi -volatile organics (including polycyclic aromatic hydrocarbons, aldehydes, polychlorinated dioxins and furans, and chlorinated biphenyls), acids (including hydrogen chloride (HCl)), and other compounds, such as ammonia (NH_3) and chlorine (Cl_2). Existing datasets measuring toxic air pollutants are even more limited than those measuring criteria air pollutants.

Metals (such as lead, cadmium, arsenic, chromium, and mercury) emissions are not typically of concern because biomass feedstocks tend to contain very low levels of these constituents. However, they may be of concern for feedstocks that are co-mingled with urban waste. The lower operating temperatures of BPS (compared with combustors and incinerators) and gentle mixing in the primary charring reactor tend to lead to binding of any metals in the biochar product, and reduce metals in the exhaust gas emissions. Add-on control devices including filters, scrubbers, and electrostatic precipitators for fine particulate matter that may be required on larger biochar production units will also provide an additional reduction of non-volatile metals.

Table 12.1. *Comparison of criteria emissions from biomass management options.*

Management Alternative	lb/ton wet biomass (actual)			
	NOx	PM	VOC	CO
Open pile burn[1,2]	3.5	8.0	6.0	75.0
Circulating fluidized bed boiler[2]	1.0	0.1	0.0	0.0
Air curtain burner[3]	1.0	1.3	0.9	2.6
Biochar Now[4]	1.0	0.1	0.1	0.1
Kon tiki kiln[5]	0.2	3.0	1.5	13.0

1 *Springsteen, B, T Christofk, R York, T Mason, D Baker, et al., Forest biomass diversion in the Sierra Nevada: Energy, economics and emissions, California Agriculture Journal, Vol 69, No 3, pp 142-149, July-September 2015.*

2 *Springsteen, B, T Christofk, T Mason, C Clavin, B Storey, Emission reductions from woody biomass waste for energy as an alternative to open burning, Journal of the Air and Waste Management Association, Vol 61, pp 63-68, January 2011.*

3 *Clerico, B, E Villegas, San Joaquin Valley Air Pollution Control District, Memo to A Marjollet, Air Curtain Emissions Factors Determination, dated April 4, 2017.*

4 *Emissions Measurement Company, Emissions Testing Report for Biochar Now, LLC, Construction Permit 15WE1395, Biochar Kilns (AIRS 001), Weld County, Colorado, Test Dates: September 6-8, 2017, Project Code BN17-0090. Data courtesy of James Gaspard.*

5 *Cornelissen, G, NR Pandit, P Taylor et al., Emissions and Char Quality of Flame-Curtain "Kon Tiki" Kilns for Farmer-Scale Charcoal/Biochar Production, PLOS ONE 11(5), May 18, 2016.*

Volatile and semi-volatile organics are a potential concern. The syngas generated during biochar production can contain high levels of volatile and semi-volatile organics resulting from the conditions used to produce biochar. For environmental and safety reasons, this syngas must be treated or processed prior to release. Efficiency (and economics) of the biochar production process may also benefit as heat can be recovered during syngas combustion. Most commonly, the syngas is burned (fully oxidized) in add-on flare or afterburners, staged combustion design internal to the reactor, or heat recovery in an engine or boiler. With proper design and operation to ensure sufficient oxygen and time at elevated temperatures, organic emissions will be very low, comparable or lower than biomass combustion units, incinerators, or oil or gas combustion.

Biomass feedstocks typically have very low chlorine levels. Any chlorine in the biomass feedstock will be predominately emitted in the form of HCl in the oxidized exhaust gas, or Cl_2 where the syngas is not fully oxidized.

Greenhouse Gases

BPS emit greenhouse gases (GHGs), including carbon dioxide (CO_2) methane (CH_4), and $PM_{2.5}$[2]. Carbon in biomass is "biogenic", and part of the active natural carbon cycle. Because the CO_2 released during biochar production has been recently captured from the atmosphere and stored in plant tissues through photosynthesis, biomass is generally considered carbon-neutral by state and federal agencies. However, other emissions are of concern—the full GHG impact depends not only on the BPS, but on emissions associated with the complete lifecycle of production and application. This includes biomass sourcing, transport and processing, the amount of carbon captured in biochar, transport and application of biochar, as well as fossil fuel offsets resulting from energy produced and captured during biochar production, and the alternative fate of the biomass without the BPS. The climate impact of biochar is discussed more fully in Chapter 1.

PERMITTING COMPLEXITY AND COST FOR BIOCHAR PRODUCTION SYSTEMS COMPARED TO OPEN BURNING

Those who are exploring the use of BPS to replace open burns in forestry and agriculture will generally find that despite the air quality benefit, the applicable regulatory process is substantially more complex, costly, and time consuming than the permitting process for open burns. For example, in the Northwest, the Department of Natural Resources (Washington) or the Department of Forestry (Oregon) provide regulatory oversight for pile or understory burning in forestry contexts. The primary aim of this oversight is to avoid violating the NAAQS. 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 $PM_{2.5}$ 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 BPS will 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. The permit for a BPS is valid for the lifetime of the operation—whereas a prescribed burn permit is issued and approved for a limited one-time burn. Thus, the BPS permitting process is likely to be substantially more time consuming and expensive compared with open pile burning.

OVERVIEW OF PERMIT TYPES FOR BIOCHAR PRODUCTION SYSTEMS

Many, if not most, BPS will fail to qualify for an exemption from air quality permitting and thus will require a permit from the appropriate agency. BPS that have the capacity to discharge emissions exceeding a specified threshold may be subject to Title V or New Source Review/Prevention of Significant Deterioration (NSR/PSD) permitting requirements. Most sites will go through some type of review to determine whether or not these permits apply, and to review, approve, and issue the required permit.

2 *Black carbon, a component of particulate matter (PM), is considered an important climate pollutant that can cause local warming and increased melting when deposited globally on ice and snow.*

New Source Review / Prevention of Significant Deterioration

The NSR/PSD regulations apply to new "stationary sources" and "modifications" of existing sources. NSR applies in nonattainment areas[3] and PSD applies in attainment areas. A "major stationary source" is any source type belonging to a list of 28 source categories which emits or has the potential to emit 100 tons per year or more of any pollutant subject to regulation under the federal Clean Air Act, or any other source which emits (or has the potential to emit) such pollutants in amounts equal to or greater than 250 tons per year (see 40 CFR 52.21(b)(1)(i)).

The PSD permitting process involves rigorous reviews of control technology and air quality impacts. However, unless a BPS is embedded within a major stationary source, it is unlikely to trigger PSD.

Title V

If a facility is designated as a major source, as defined in 40 CFR 70.2, it will need a federally enforceable Title V permit. A major source has actual or potential emissions at or above the major source threshold for any air pollutant subject to regulation. The major source threshold for any air pollutant is 100 tons per year. Lower thresholds apply in non-attainment areas (but only for the pollutants that are in non-attainment). Major source thresholds for hazardous air pollutants (HAP) are 10 tons per year for a single HAP or 25 tons per year for any combination of HAP.[4]

However, regardless of the level of potential emissions, biochar production facilities that are defined as incinerators are subject to one of the federal incinerator rules and will therefore require Title V permitting. For distinct units at commercial or industrial facilities, the Commercial and Industrial Solid Waste Incineration Units (CISWI) rule normally applies. For units that combust waste collected from the public or from multiple facilities, the small municipal solid waste incinerator rule or the Other Solid Waste Incinerators (OSWI) rule may apply. Incinerators are subject to strict emissions limits, as well as requirements for source testing, development of operating and monitoring parameters, and extensive reporting.[5]

Further guidance about whether a pyrolysis unit is an incinerator is available in 40 CFR 241, which identifies the requirements and procedures for the identification of solid wastes used as fuels or ingredients in combustion units under Section 1004 of the Resource Conservation and Recovery Act and Section 129 of the Clean Air Act. By law, units are incinerators if they combust any solid waste.[6] According to 40 CFR 241, clean cellulosic biomass, including materials such as virgin wood and agricultural residues, are not considered to be solid waste. Gases are not normally considered solid waste unless they are contained (such as gases in a discarded propane canister). When the biomass feedstock to a BPS stays under the control of the facility being permitted, then the facility can self-certify whether or not the secondary material is a fuel or a waste, after considering the definitions and procedures in 40 CFR 241.

Air curtain incinerators (ACI) represent a special category of BPS, as they are defined within section 129 of the Clean Air Act as incinerators. They will, therefore, be subject to one of the federal incinerator standards (with a limited set of requirements) and will be required to obtain Title V permits.[7] Oregon is trying to reduce this burden by creating a Title V general permit, which would allow owners and operations to obtain permits more easily and at a lower cost.[8] In August 2020, the EPA proposed a rule change to exempt ACI from Title V permitting where they process virgin forest materials.

NSR Permit

The Clean Air Act and its implementing regulations require each state to prepare a plan to ensure that the construction or modification of sources of air pollution will not result in violations of restrictions on air pollution or attainment or maintenance of the NAAQS.[9] On tribal lands, the EPA has established minor source permitting requirements in the *Federal*

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3 A nonattainment area is an area where concentrations of a criteria air pollutant exceed the NAAQS. The boundaries of non-attainment areas are proposed by the state and approved the EPA.

4 In this case, the list of HAP is limited to those air toxics identified in section 112 of the Clean Air Act.

5 See 40 CFR part 60, subparts AAAA and BBBB for requirement that may apply to small municipal solid waste incinerators, subparts CCCC and DDDD of CISWI units, and subparts EEEE and FFFF for OSWI units.

6 Natural Resources Defense Council et al. vs. EPA, Case No. 04-1385 (D.C. Circuit, June 8, 2007)

7 Because this requirement is in the Clean Air Act, changing it would require an act of Congress.

8 General Title V permits are allowed under 40 CFR 70.6(d).

9 See Clean Air Act sections 110(a) and 110(j). Also, 40 CFR part 51, subpart I.

(Map via https://www.arb.ca.gov/capcoa/dismap.htm)

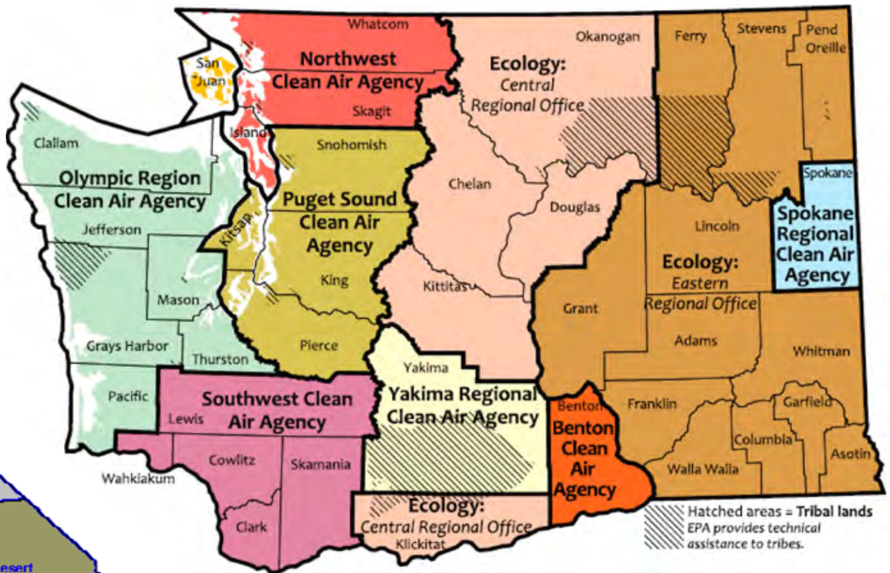

Figure 12.1. *(left) Map of California air districts.*
Figure 12.2. *(above) Map of Washington air districts.*

Minor New Source Review Program in Indian Country.[10] The threshold for permitting and the requirements of NSR vary significantly from permitting authority to permitting authority, even between different authorities within the same state.

In California, Oregon, and Washington, the review process for a BPS may include:

- A demonstration that the proposed equipment will comply with all applicable requirements, including federal standards (if any) and state prohibitory rules;
- A determination of the appropriate control technology;
- Quantification of emissions of all regulated air pollutants;
- A demonstration that additional emissions will not result in an exceedance of the NAAQS;
- A review of air toxics emissions and impacts (each state has its own health-based air toxics control program);
- In nonattainment areas (including in much of California) a requirement to offset new emissions;
- There may be an initial state-required siting review (such as CEQA in California or SEPA in Washington); and
- State-required GHG programs if applicable.

In some areas, including in California and Oregon, the NSR permitting process is divided into separate construction and operating permits. In other areas, such as Washington and tribal lands where the EPA issues the permits, there is a single permit that allows both construction and operation. However, it would be possible for state, local, and tribal agencies to issue a general NSR permit for classes of air pollution sources or implementing permit-by-rule, which allows equipment that meets certain criteria and complies with a set of standardized requirements to avoid permitting.[11]

To better understand local NSR permitting requirements, it is important to contact the permitting authority early in the process.

- In California, there are 35 local permitting authorities. See Figure 12.1 for more information.
- In Oregon, the Oregon Department of Environmental Quality issues permits except in Lane

10 *See 40 CFR 49,151 through 49.165.*

11 *Tribal Minor New Source Review:* https://www.epa.gov/tribal-air/tribal-minor-new-source-review

County, where permits are issued by the Lane Regional Air Protection Agency.

- In Washington, there are seven local permitting authorities. The Department of Ecology issues permits in many rural areas and under special circumstances. See Figure 12.2 for more information.
- EPA Region 9 issues air permits on tribal lands in Arizona, California, and Nevada.
- EPA Region 10 issues air permits on tribal lands in Alaska, Idaho, Oregon, and Washington.

To illustrate how the permitting process can play out at the local level, and the complexity that represents a barrier to BPS adoption, the sidebar ("A Case Study of the Permitting Process for a Biochar Production System in California" on page 163) provides more information relevant to permitting of BPS in California, which is among the more time-consuming processes in the western U.S.

THE ROLE OF EMISSIONS DATA IN PERMITTING

The level of emissions of both criteria pollutants and toxic air pollutants directs decisions throughout the permitting process, from whether and what type of permitting is needed, to identification of the most important criteria and toxic air pollutants that will be the permitting focus.

As previously discussed, one challenge to quantifying emissions of BPS is that emissions from biochar production units can be quite variable, depending on feedstock type, composition (including moisture content), and equipment parameters. This adds complexity to the task of developing a regulatory framework applicable to biochar—though in some cases, there are fairly straight-forward rules of thumb that can help reduce emissions (for example, processing dry feedstocks will generally reduce emissions compared to wet feedstocks).

A second challenge relates to the dearth of existing data measuring emissions of criteria pollutants and toxic air pollutants from BPS. In evaluating emissions rates for new sources, permitting agencies prefer source test performance data from similar units to the one being proposed. However, lacking this data, alternatives can be considered, such as the use of data from biomass or fossil fuel combustors, and/or engineering mass balance estimates based on feedstock composition. For criteria air pollutants, permits would most likely require source testing following installation of the BPS to demonstrate compliance with permit emission limits, and may require subsequent periodic source tests (for example, every 3 years).

When air agencies can rely on existing datasets to derive emissions factors that can be applied, this can speed the permitting process and greatly reduce costs. These costs are a concern for BPS at all scales, but can be a particular concern for smaller biochar production systems operating in resource-limited contexts. However, it can be difficult to utilize emissions factors for BPS, as existing emission data are limited for criteria pollutants for many (though not all) types of biochar production units; emission data are lacking for toxic air pollutants for all types.

Depending on the pollutants of interest, indirect sampling may be an option in some cases, and can reduce analytical complexity and cost compared to direct measurement. For metals (if suspect feedstocks such as urban waste are used) and for HCl, strategic feedstock sampling and analysis can be a very cost-effective alternative to stack sampling. For organics, an effective and commonly used alternative to speciated organics measurements is to use measurements of CO and total volatile organic compounds as surrogate indicators for complete combustion.

Given the lack of data, source testing may be required. While on the one hand, this process will generate data that may be helpful for others, it can be prohibitively expensive in some cases. However, in the absence of more specific data, permit writers tend to make conservative assumptions, which may overestimate the risk. This in turn results in more constrictive operational parameters, such as the minimum acceptable distance to a home, park, or other site of an individual who may be harmed by the pollution.

It is also likely that in a context in which there is limited-to-no existing data to help guide which toxics are of potential concern, variability in permitting approach from jurisdiction to jurisdiction will be particularly high. Depending on the specific biochar production process, toxic air pollutants which may potentially be of concern include acrolein, formaldehyde, acetaldehyde, benzene, trace metals, polycyclic aromatic hydrocarbons (PAH), dioxins, furans, and miscellaneous constituents including hydrogen chloride and ammonia. The list of potential concerns is currently large, so improvements in knowledge could also help narrow the focus to those most likely to be problematic.

If permitting is needed, emissions of one or a few potential criteria pollutants and one or a few potential toxic air pollutants generally drive the permitting process. The particular compound or compounds depend on the specific emission profile of the BPS, the air quality issues that are most important in the location(s) in which the BPS will operate, and the

A Case Study of the Permitting Process for a Biochar Production System in California

In California, an "Authority to Construct" (ATC) (or "Notice of Construction Permit") application must be submitted prior to facility construction. This application, prepared by the BPS developer, would contain a thorough description of the equipment, operation, and anticipated emissions. This application is submitted to the local regulatory agency responsible for air quality permitting. The application is then reviewed by the regulatory agency to ensure compliance with all applicable requirements, including New Source Review (NSR), prohibitory rules, and air toxics. These requirements, as discussed in more detail below, depend on the air quality attainment status of the siting location.

Best Available Control Technology

Under NSR, the use of Best Available Control Technology (BACT) may be required. Examples of BACT emissions thresholds in California Air Districts are shown in Table 12.5. The site-specific determination of BACT will be based on the most effective controls used (with lowest emissions levels achieved in practice) at similar existing facilities, or another control determined to be technologically feasible and cost effective. For larger BPS plants, this might require PM control with baghouse filters, electrostatic precipitators, or scrubbers, CO and reactive organic gas (ROG)[1] control through combustion air and fuel adjustments, and NOx control through selective non-catalytic reduction or selective catalytic reduction.

Offsets

For areas in non-attainment with ambient air quality standards, NSR may also require emissions "offsets". Much of the State of California is in non-attainment with ozone ambient air quality standards, thus offsets may be required for ROG and NOx in these locations. Offsets levels required are the difference between actual emissions after BACT and the specific offset threshold (shown in Table 12.5). Offsets are typically obtained through the purchase of Emission Reduction Credits (ERC). ERC represent previously reduced emissions, usually from other facilities, and must be shown to be in addition to any requirement under the law (surplus), documented through records (quantifiable), and have mechanisms to ensure reductions will continue in the future (enforceable and permanent). ERC must be obtained from sources within the same air basin as the biomass source, and can be required at a greater than 1-to-1 ratio, depending on the distance from the BPS and the site(s) where individuals may be impacted by emissions.

Health Risk Assessment

The regulatory agency will also likely require a health risk assessment (HRA) based on air toxics emissions. An HRA requires quantification of both the acute health risk from short-term exposure to high pollutant concentrations, and chronic non-cancer and cancer risk from long-term exposure for all air toxics that are emitted. This is performed using air dispersion modeling, requiring local meteorology data including wind speed and direction, and identification of local and sensitive receptors. Typical allowable additional risks are a cumulative cancer risk of less than ten in one-million, and a hazard index (for non-cancer constituents) of less than one.

Prohibitory Rules

There may also be prohibitory rules that apply to BPS, particularly limitations for boilers and internal combustion engines for CO, NOx, and/or PM. Typically, BACT and offset requirements are ultimately as or more stringent. BPS units also will need to meet general nuisance rules, which provide authority to the regulatory agency to control the discharge of any air contaminants that is determined to cause injury, detriment, endangerment, discomfort, annoyance, or which have a natural tendency to cause damage to business or property (California Health and Safety Code Section 41700; Placer County Air Pollution Control District Rule 205, Nuisance), and opacity limits,

Table 12.5. *Best Available Control Technology (BACT) and offset thresholds for selected local California Air Quality Agencies*

Local Air Quality Agency	BACT Threshold (lb/day)				Offset Threshold (tons/yr)			
	PM	NOx	CO	ROG	PM	NOx	CO	ROG
Feather River	80	10 / 25	500	10 /25		10 / 25		10 / 25
Butte Co.	80	25	500	25		25		25
El Dorado Co.	80	10	550	10	15	10	15	10
Placer Co.	80	10	550	10	15	10	99	10
Tehama Co.	80	25	500	25		25		25
Shasta Co.	80	25	500	25		25		25
N. Coast Unified	80	50	500	50		25		25

PM = particulate matter; NOx = nitrogen oxides; CO = carbon monoxide; ROG = reactive organic gasses

1 *Reactive Organic Gases (ROG) is a term used by and defined by the California Air Resources Board. While it includes many of the compounds included on the list of Volatile Organic Compounds (VOC) as used by the U.S. Environmental Protection Agency (EPA), it also includes low-reactive organic compounds which have been exempted by the EPA.*

specific regulatory process in a given location. As one example, existing emissions data for a Biochar Now unit are shown in Table 12.2. If such a unit were to be installed in Placer County, California, comparison of the emissions values with the Best Available Control Technology (BACT) thresholds and the Emissions Reduction Credits (ERC) thresholds for this location (Table 12.3 and Table 12.4, respectively) indicates that NOx is the most important of the criteria pollutants for this situation, with BACT required for greater than ten units, and ERC purchase required if more than 50 units were operated in a single location.

Illustrating the importance of location and regulatory context, if such a unit were installed Skagit County, Washington, a permit would not be required based on the potential emissions profile shown in Table 12.2.

Table 12.2. *Emissions data for a Biochar Now unit (Gaspard, unpublished data).*

Pollutant	Actual Emissions (per kiln) lb/hr	Potential Emissions (per kiln)		Emission Factor lb/ton material
		lb/day	tons/year	
NOx	0.13	1.17	0.214	1.04
PM	0.016	0.14	0.026	0.13
VOC	0.01	0.09	0.016	0.08
CO	0.0072	0.06	0.012	0.06

Table 12.3. *Best Available Control Technology (BACT) thresholds for select Air Districts in California, in April 2020.*

	BACT Threshold (lb/day)		
Pollutant	Placer	San Joaquin	Shasta
NOx	10	2	25
PM	10	2	25
VOC	80	2	80
CO	550	2	500

Table 12.4. *Emissions Reduction Credit (ERC) thresholds for select Air Districts in California, in April 2020.*

	ERC Threshold (tons/yr)		
Pollutant	Placer	San Joaquin	Shasta
NOx	10	10	0
PM	10	10	0
VOC	15	15	0
CO	99	100	0

PORTABLE OR TEMPORARY BIOCHAR UNITS

Portable or temporary BPS 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.

Continued from "A Case Study of the Permitting Process for a Biochar Production System in California" on page 163.

which limit opacity to no more than 3 minutes of opacity greater than 20% in any one hour (e.g., Placer County Air Pollution Control District Rule 201, Visible Emissions).

California Environmental Quality Act

An evaluation under the California Environmental Quality Act (CEQA) may be required if it is concluded that the biomass project has a significant impact on the environment. CEQA review involves an analysis of the environmental impacts of the project, the alternatives, and consideration that significant impacts are mitigated to the extent feasible. For a biomass conversion unit, alternatives to be analyzed may include different siting locations and different biomass disposal options such as open pile burn, on-site grinding, and/or air curtain destructors. The analysis must incorporate all significant effects of facility construction, indirect emissions from mobile source activity, and the cumulative impacts of other emission sources in the area.

Greenhouse Gas Emissions

The California Air Resources Board (CARB) requires the annual reporting of GHG from sources, including biomass, that emit GHG of greater than 25,000 metric tonnes annually. Under the CARB GHG cap-and-trade program, GHG from biomass combustion are considered carbon neutral, and will not require allowances. This is consistent with other regional programs, and international and federal guidance. A consideration of GHG impacts may also be required under CEQA review.

Permit to Operate

Following facility construction and startup operation, and a regulatory agency inspection, a full Permit to Operate (PTO) will be issued. The PTO is a legally binding document that includes enforceable conditions with which the biomass plant operator must comply. It contains a detailed list of requirements including those related to the facility operation (such as material throughput limits, pressure and temperatures, and conditions on the operation of the air pollution control devices), emissions limitations, monitoring and testing procedures, and recordkeeping and reporting. ■

Though 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 an issue. 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.

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