CHAPTER 5:

Moderate-Scale Biochar Production Across Forested Landscapes

James Dooley, Han-Sup Han, Marcus Kauffman, John Miedema, Deborah S. Page-Dumroese, and Carlos Rodriguez-Franco

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).

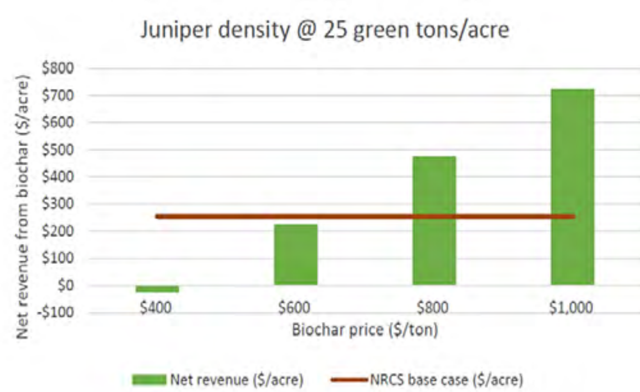

Figure 5.2. *Costs and capacities of moderate scale biochar production technologies. (Delaney & Miles 2019)*

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 ($)	$/ft³	$/yd³
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).

REFERENCES

Buford A.M., & Neary, D.G. (2010). Sustainable Biofuels from Forests: Meeting the Challenge, *The Ecological Society of America*. http://esa.org/biofuelsreports.

Burns, C., Lykes, V.A., Steinmann, F.A., & Kauneckis, D. (2014). The Economics of Biochar Production: A Review. University Center for Economic Development, College of Business, University of Nevada, Reno. Technical Report UCED 2014/15-09. 14p. https://www.unr.edu/Documents/business/NLI/Projects/The_Economics_of_Biochar_Production_-_A_Review_UCED_2014-15-09.pdf

Campbell, R.M., Anderson, N.M., Daugaard, D.E., & Naughton, H.T. (2018). Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. *Applied Energy*, *230*, 330-343. https://doi.org/10.1016/j.apenergy.2018.08.085

Certini, G. (2005). Effects of fire on properties of forest soils: A review. *Oecologia*, 143,1-10. https://doi.org/10.1007/s00442-004-1788-8

Delaney, M. & Miles, T. (2019). Economics of mobile and stationary biochar production systems using juniper feedstocks in Oregon Report. Prepared for USDA ARS JuBop project. 15p.

Dooley, J.H., Lanning, C., & Lanning, D.N. (2011). Modeling energy consumption for crushing of roundwood as a first stage of feedstock preparation. ASABE Paper No. 1111085. St. Joseph, MI, American Society of Agricultural and Biological Engineers: 17. https://doi.org/10.13031/2013.37414

Dovetail, Inc. (2018). Survey and Analysis of the US Biochar Industry. Dovetail Partners Inc., 25p. http://www.dovetailinc.org

Draper, K. (2019). Biochar Labeling & US Certifications. https://pyrolist.com/blog/biochar-labeling-us-certifications. [Accessed March 3, 2020].

Dumroese, R.K., Page-Dumroese, D.S., & Pinto, J. (2020). Biochar potential to enhance forest resilience, seedling quality, and nursery efficiency. *Tree Planters' Notes*, *63* (1), 61-68

EBC. (2012). 'European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.' European Biochar Foundation (EBC), Arbaz, Switzerland. Version 6.2E of 04th February 2016, DOI: 10.13140/RG.2.1.4658.7043. https://www.zora.uzh.ch/id/eprint/125910/1/2016_ebc-guidelines.pdf

Garcia-Nunez, J.A., Palaez-Samaniego, M.R., Garcia-Perez, M.E., Fonts, I., Abrego, J., Westerhof, R., & Garcia-Perez, M. (2017). Historical developments of pyrolysis reactors: A review. *Energy & Fuels*, 31(6), 5751-5775. https://doi.org/10.1021/acs.energyfuels.7b00641

Garcia-Perez M., Garcia-Nunez, J.A., Lewis, T., Kruger, C.E. & Kantor, S. (2011). Methods for Producing Biochar and Advanced Bio-fuels in Washington State. Part 3: Literature Review of Technologies for Product Collection and Refining. Third Project Report. Department of Biological Systems Engineering and the Center for Sustaining Agriculture and Natural Resources, Washington State University, Pullman, WA. http://www.pacificbiomass.org/

Han, H-S., Jacobson, A., Bilek, E.M., & Sessions, J. (2018). Waste to Wisdom: Utilizing forest residues for the production of bioenergy and biobased products. *Applied Engineering in Agriculture*, 34(1), 5-10. https://www.fpl.fs.fed.us/documnts/pdf2018/fpl_2018_han001.pdf

IBI. (2015). International Biochar Initiative, Standardized Product Definition and Product Testing Guidelines for Biochar that is used in Soil. Final Version. http://www.biochar-international.org/characterizationstandard

Isaac, L.A., & Hopkins, H.G. (1937). The forest soil of the Douglas-Fir Region, and changes wrought upon it by logging and slash burning. *Ecology*, 18, 264-279. https://doi.org/10.2307/1930465

Klinar, D. (2016). Universal model of slow pyrolysis technology producing biochar and heat from standard biomass needed for the techno-economic assessment. Biomass Technology, 206: 112-120. http://dx.doi.org/10.1016/j.biortech.2016.01.053

McCulloch, W.F. (1944). Slash burning. *Forestry Chronicle*, 20, 111-118. https://doi.org/10.5558/tfc20111-2

Miller, C.A., & Lemieux, P.M. (2012). Emissions from the burning of vegetative debris in air curtain destructors. *Journal of Air & Waste Management Association*, 57, 959-967. https://doi.org/10.3155/1047-3289.57.8.959

Mohan, D., Pittman, U.C., & Steele, H.P. (2006). Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy & Fuels* 2006 *20* (3), 848-889. https://doi.org/10.1021/ef0502397

Novak, J.M., Ippolito, J.A., Lentz, R.D., Spokas, K.A., Bolster, C.H., Sistani, K., Trippe, K.M., Phillips, C.L, & Johnson, M.G. (2016). Soil health, crop productivity, microbial transport, and mine spoil response to biochars. *BioEnergy Research*, *9*, 454-464. https://doi.org/10.1007/s12155-016-9720-8

NRCS. (2020). United States Department of Agriculture, Natural Resource Conservation Service. https://www.climatehubs.usda.gov/hubs/northeast/news/new-nrcs-practices-address-climate-change-issues. [Accessed June 2, 2020.]

Page-Dumroese, D.S., Busse, M.D., Archuleta, J.G., McAvoy, D., & Roussel, E. (2017a). Methods to reduce forest residue volume after timber harvesting and produce black carbon. *Scientifica*, 2745764, 8p. https://www.hindawi.com/journals/scientifica/2017/2745764/

Page-Dumroese, D.S., Coleman, M.D., & Thomas, S.C. (2017b). Opportunities and uses of biochar on forest sites in North America [Chapter 15]. In: Bruckman, Viktor; Varol, Esin Apaydin; Uzun, Basak; Liu, Jay, eds. Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation. Cambridge, UK: Cambridge University Press. p. 315-335.

Page-Dumroese, D.S., Ott, M.R., Strawn, D.G., & Tirocke, J.M. (2018). Using organic amendments to restore soil physical and chemical properties of a mine site in northeastern Oregon, USA. *Applied Engineering in Agriculture*, 34(1), 43-55. https://doi.org/10.13031/aea.12399

Prescient and Strategic (P&S) Intelligence Private. (2015). Global Biochar Market Size, Share, Development, Growth and Demand Forecast to 2023 – Industry Insights by Application (Gardening, Agriculture, Household), Feedstock (Agriculture Waste, Forestry Waste, Animal Manure, and Biomass Plantation), Technology (Microwave Pyrolysis, Batch Pyrolysis Kiln, Gasifier and Cookstove, and Others), Manufacturing Process (Gasification, Fast and Intermediate Pyrolysis, Slow Pyrolysis, and Others). https://www.psmarketresearch.com/market-analysis/biochar-market [Accessed 05/21/2019].

Puettman, M., Sahoo, K., Wilson, K., & Oneil, E. (2019). Life cycle assessment of biochar produced from forest residues using portable systems. *Journal of Cleaner Production* 250, 119564, https://doi.org/10.1016/j.jclepro.2019.119564

Ramlow, M., Rhoades, C.C., & Cortrufo, M.F. (2018). Promoting revegetation and soil carbon sequestration on decommissioned forest roads in Colorado, USA: A comparative assessment of organic soil amendments. *Forest Ecology and Management*, 427, 230-241. https://doi.org/10.1016/j.foreco.2018.05.059

Rodriguez-Franco, C., & Page-Dumroese, D.S. (2021). Woody biochar potential for abandoned mine land restoration in the U.S.: A review. *Biochar*. https://doi.org/10.1007/s42773-020-00074-y

Sahoo, K., Bilek, E., Bergman, R. & Mani, S. (2019). Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. *Applied Energy*, 235, 578-590. https://doi.org/10.1016/j.apenergy.2018.10.076

Sarauer, J.L., Page-Dumroese, D.S., & Coleman, M.D. (2019). Soil greenhouse gas, carbon content, and tree growth response to biochar amendment in western United States forests. *GCB Bioenergy*, 11(5), 660-671. https://doi.org/10.1111/gcbb.12595

Thomas, S.C., & Gale, N. (2015). Biochar and forest restoration: A review and meta-analysis of tree growth responses. *New Forests*, 46(5-6), 931-946. https://doi.org/10.1007/s11056-015-9491-7

U.S. Department of Energy. (2016). 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. https://doi.org/10.2172/1271651

U.S. Environmental Protection Agency (USEPA). (2001). Emergency Planning and Community Right-to-Know Section 313. https://ofmpub.epa.gov/apex/guideme_ext/guideme/file/pesticides%20and%20persistant%20bioaccumulative%20toxic%20(pbt)%20chemicals.pdf

U.S. Environmental Protection Agency (USEPA). (2008). Polycyclic Aromatic Hydrocarbons (PAHs). https://archive.epa.gov/epawaste/hazard/wastemin/web/pdf/pahs.pdf

U.S. Environmental Protection Agency (USEPA). (2021). Air Emissions Monitoring for Permits. Accessed February 18, 2021. https://www.epa.gov/air-emissions-monitoring-knowledge-base/air-emissions-monitoring-permits#:~:text=The%20Clean%20Air%20Act%20Amendments,program%20for%20the%20federal%20government.&text=Title%20V%20permits%20are%20federally,State%20or%20local%20permitting%20authorities.

Verheijen, F., Jeffery, S., Bastos, A.C., van der Velde, M., & Diafas, I. (2010). Biochar application to soils: A critical scientific review of effects on soil properties, processes and functions. European Commission. http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/EUR24099.pdf

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications* 1, 56. https://doi.org/10.1038/ncomms1053

Zhu, Q.H., Peng, X.H., Huang, T.Q., Xie, Z.B., & Holden, N.M. (2014). Effect of biochar addition on maize growth and nitrogen use efficiency in acidic red soils. *Pedosphere*, 24, 699–708. https://doi.org/10.1016/s1002-0160(14)60057-6