Technical Assessment of Potential Climate Impact and Economic Viability of Biochar Technologies for Small-Scale Agriculture in the Pacific Northwest

Report Submitted to

Steward Holdings, LLC

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1. Introduction

Challenges facing small-scale agriculture include climate variability and warming, withering of local community structures and economies, and shrinking profit margins. Because of its potential to enhance soil health and productivity while sequestering carbon (C) across a wide range of scales, and thereby to provide a new source of income in the form of C credits to agricultural operators, biochar technology has been suggested as one way of addressing these challenges. This report provides an overview and technical assessment of the viability of the biochar technology approach when implemented at the small-scale in the Pacific Northwest (PNW) region of the United States (USA). In this section, we provide background information for the major issues considered in the report.

1.1. Climate Change

Significant changes in the climate of the PNW that affect agriculture are expected for the remainder of this century (May et al. 2018; Frankson et al. 2022a, 2022b; Runkle et al. 2022). Average temperatures, which have already increased by 2°F to 2.5°F above pre-industrial levels, are projected to increase by an additional 3°F to 6°F (depending on global emissions scenarios) by the year 2100. Precipitation patterns will change, with 5-10% more winter and spring precipitation coupled with 5-10% less summer precipitation (Figure 1). Rain will become the dominant form of precipitation and snowpack will decrease significantly (by as much as 70% in Washington State). The shift to more spring precipitation and earlier snowpack loss will increase the frequency and severity of flooding in the late spring and early summer. As many as 80% of the river basins in the PNW will see decreases in summer stream flows. The net result of these climatic changes will be more summer droughts and heat waves coupled with decreases in the quantity of water available for late summer irrigation.

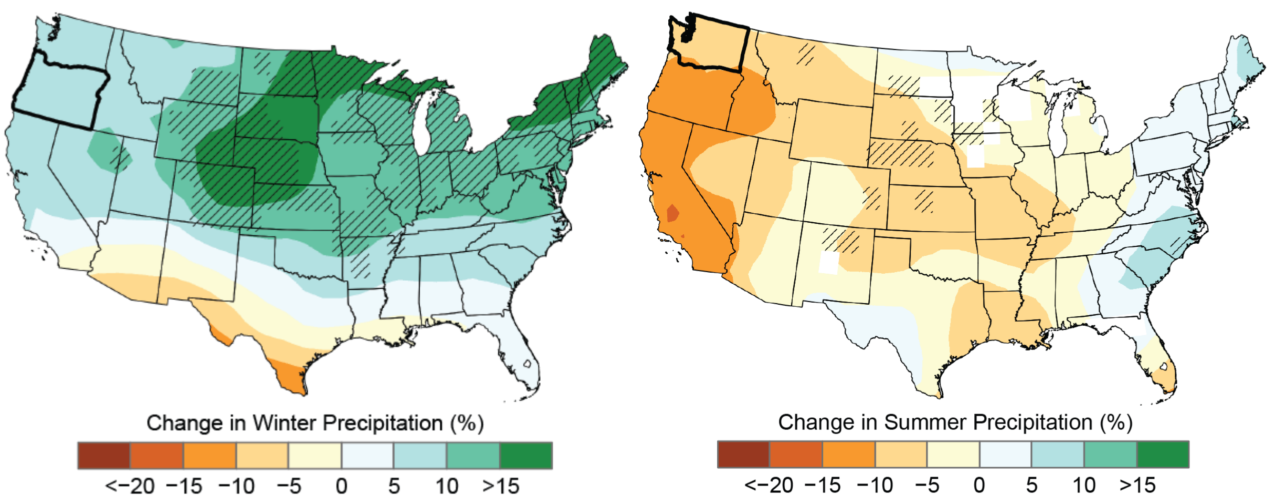


Figure 1. Projected changes in total winter (December-February) and summer (June–August) precipitation (%) for the middle of the 21st century compared to the late 20th century under a higher emissions pathway (Frankson et al. 2022a, 2022b).

These climatic changes are driven by increased emissions of long-lived greenhouse gases and aerosols (GHG/A) stemming from human activity (USGCRP 2017; Eyring et al. 2021). The primary GHG/As of concern are carbon dioxide (CO_2), which is responsible for 70% of the climate impact, methane (CH_4), nitrous oxide (N_2O), and soot (a charcoal-like particulate aerosol generated by pyrolysis and combustion). The climate impacts of these GHG/As are ranked by their global warming potential (GWP), which accounts for differences in their atmospheric lifetime and intrinsic ability to absorb solar radiation relative to CO_2. Thus, CO_2 always has a GWP of 1. The GWPs for the other

GHG/As vary according to the timeframe considered (Figure 2). For example, a single pulse of CH_4 into the atmosphere will yield GWPs of 134 in the first year, 91 in the 20th year, and 30 after 100 years (Table 1), indicating that emission of a kg of CH_4 is equivalent to the emission of 134, 91, or 30 kg of CO_2, respectively, 1, 20, or 100 years after emission. Nitrous oxide is a more powerful GHG, with GWPs of 234, 291, and 300 for the same three time periods. Most life cycle assessments (LCAs) include these three GHGs in their climate-focused calculations.

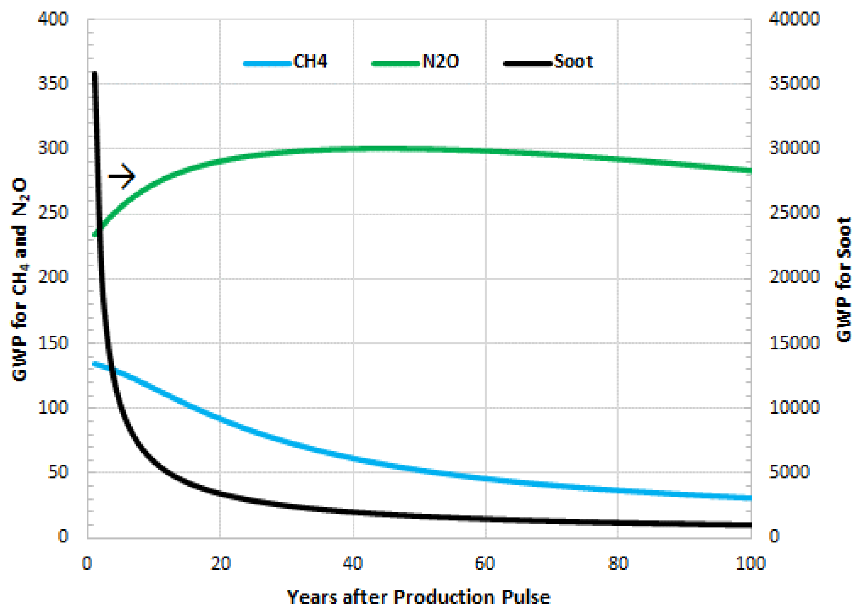


Figure 2. Changes in GWPs for CH_4, N_2O and soot during the first hundred years after emission of a single pulse into the atmosphere. Note the 100-fold difference in axis scaling for soot (right axis). The GWP for CO_2 (not shown) is always 1 (Myhre et al. 2013; Bond et al. 2013).

Table 1. Global warming potentials for CH_4, N_2O and soot 1, 20, 50, and 100 years after emission of a single pulse into the atmosphere (Myhre et al. 2013; Bond et al. 2013).

GHG/A	Timeframe, years after emission 1	20	50	100
	-------------- t CO2e / t GHG/A --------------			
CH_4	134	91	52	30
N_2O	234	291	300	283
Soot	35800	3350	1630	940

Because soot is a "greenhouse aerosol" (GHA) with a relatively short atmospheric lifetime (about a week) it is often overlooked in LCAs. Nevertheless, soot strongly absorbs solar radiation while suspended in the atmosphere or deposited on the earth's surface (Ramanathan and Carmichael 2008; Ramana et al. 2010; Bond et al. 2013). It is of particular concern due to its ability to significantly lower the albedo (the fraction of solar radiation striking the earth's surface that is reflected into space) of glaciers and the polar ice caps. Despite its short atmospheric lifetime, the warming effect of soot is comparable to that of a long-lived greenhouse gas with a first year GWP of 36000, a 20-year GWP of 3300, and a 100-year GWP of about 900 (Figure 2, Table 1). The amount of soot emitted by a combination of human activity and naturally caused wildfires is large enough to make soot second only to CO_2 in its overall impact on global climate (Bond et al. 2013). In this report, we include all four GHG/As in our LCA calculations and we strongly recommend that carbon registries factor these warming impacts into their calculations of carbon credits for bioenergy and biochar production.

The climate impact of all the GHG/As for a given timeframe is typically summarized in terms of the equivalent amount of CO_2 (CO2e) required to obtain the same warming. This value is obtained by multiplying the mass of each GHG/A by its GWP and then summing the products:

$$mCO2e_{yyy} = mCO_2 + mCH_4*GWP_{(CH4)yyy} + mN_2O*GWP_{(N2O)yyy} + mSoot*GWP_{(Soot)yyy}$$

where m refers to the mass (typically units of tonnes, or t) and the subscript for GWP indicates the GHG/A and the timeframe in years. Carbon credits usually consider a 100-year timeframe and thus are specified in t $CO2e_{100}$.

1.2. Small-Scale Agriculture and Rural Economies

Small family farms with $350,000 or less in gross cash farm income accounted for 20% of the value of U.S. farm production, and 89% of U.S. farms in 2020, operating almost half of U.S. farmland to produce a wide variety of commodities from fresh fruits, vegetables, and flowers to meats, dairy products, grains, and seed crops (USDA ERS 2022). Households operating these farms typically rely on off-farm income as well as on-farm income, though evidence from surveys suggests that the on-farm income can be important to these families and communities (Ostrom and Donovan 2013). These farm-businesses are critical to rural economies. Rural small businesses, farm businesses among them, have created roughly two-thirds of new jobs in rural America (Small Business Majority, 2019) and play a crucial role in supporting the economic, social, and environmental wellbeing of their communities. In at least some states of the Pacific Northwest, women-owned farms, immigrant-owned farms, and direct-marketing farms have been among the fastest-growing agricultural sectors and are well represented among small and very small farms (Ostrom and Donovan 2013).

Small farms and small farm operators are diverse but many face at least some common challenges, including limitations in available labor and expertise, and low access to capital. These challenges are exacerbated by the fact that these farms have historically received a disproportionately small share of public agricultural assistance dollars (Ostrom and Donovan 2013; USDA 1998). Although their number is relatively stable, small farms have accounted for decreasing shares of agricultural land and overall production since 2011 (USDA-ERS 2022) and the financial risk associated with their operation has increased.

1.3. Biochar Technology

Biochar is, in the simplest terms, charcoal made from biomass. The process of making biochar requires heating the biomass in the absence of oxygen gas (O_2), or at low O_2 levels (well below those required to completely combust the biomass), to temperatures of 325°C to 800°C (550°F to 1400°F). During the process, most of the structural oxygen (O) and hydrogen (H) and at least half of the C originally present in the biomass are released to the atmosphere. Heat is also generated. The solid product that remains (biochar) has a higher C content than the original biomass and, because the C is incorporated into a chemical structure that is completely different from and substantially more stable than the original biomass, will persist for centuries to millennia. Because a wide variety of feedstocks and process conditions can be used to make biochar (Figure 3), it must be considered a class of materials rather than a specific, well-defined substance.

Biochar is usually safely stored by adding it as a fine-grained material to soils, where it may confer a variety of benefits including stimulation of soil organic matter formation, increase in water-holding capacity, and enhancement of soil health. In the present context, the role of biochar technology is to optimize the sustainable production and harvest of biomass, its conversion to biochar, and the storage of this biochar in agricultural soils to maximize its climate mitigation potential while providing these other benefits.

Figure 3. A diverse collection of biochars made from different feedstocks by a variety of production methods (University of California-Davis Biochar Database; http://biochar.ucdavis.edu/).

1.4. Carbon Offset Mechanisms

Carbon offsets are generated from activities that avoid or remove greenhouse gas emissions. Eligible activities are determined by independent carbon registries as part of voluntary or compliance carbon markets. Carbon registries establish the rules - referred to as Methodologies or Protocols - that govern project documentation, credit quantification, and project verification. Methodologies determine how projects meet fundamental carbon quality standards, including *additionality* (activities must exceed legal requirements/compliance obligations and go beyond standard practices), *permanence* (activities must maintain emissions reductions or drawdown for a given duration), *measurability* (activities must provide evidence that real emissions reductions have occurred), *transparency*, and *verifiability* (typically by an accredited third party). A workable, scientifically credible biochar methodology that is recognized by established carbon buyers represents critical market infrastructure for scaling biochar carbon offset project development.

Once a Methodology has been established, carbon offsets can be bought and sold in the voluntary market (similar, in many respects, to a stock exchange) or compliance markets (organized by a governmental authority). The carbon offsets specify the amount of $CO2e$ generated by a given project over a specific period. Typically, these "carbon credits" are in tonnes $CO2e_{100}$. Funds from the purchase of the carbon credits are then transferred to the seller (owner of the project) who may in turn distribute some of or all the funds to upstream generators of the carbon credits (e.g., agricultural producers or cooperatives). Currently, the price of carbon credits on the voluntary market is low (< $10 for last quarter of 2022, https://carboncredits.com/carbon-prices-today/), and, of course, varies with the quality of the credits as determined by the applicable Methodology.

1.5. Goals and Scope

The goal of this study is to evaluate the state of biochar technology and determine the feasibility of integrating small-scale biochar production in ways that benefit smaller, diversified producers. Because of the emergence of carbon markets, this innovative climate and agricultural solution may be financed externally, making biochar more accessible to the growers that could benefit. In the sections that follow, we review the current state of biochar technology (Section 2), methods for assessing the potential climate impacts derived from its implementation (Section 3), and the current state of carbon-offset mechanisms for biochar technology (Section 4). In Section 5, we apply this knowledge to several specific biochar technology scenarios involving combinations of different feedstocks, production methods, and economic incentives to arrive at estimates of climate-mitigation impacts and costs per carbon credit generated. We conclude with a summary in Section 6.

2. Biochar Technology

Biochar technology encompasses several coupled processes starting with feedstock acquisition and pre-treatment, continuing with biochar (and bioenergy) production and post-production treatment of the biochar, and concluding with incorporation of the biochar into soil. In this section we provide an overview of the aspects of biochar technology having the most relevance to small-scale agricultural operations in the Pacific Northwest (PNW). We also discuss the potential economic and climate benefits stemming from integration of biochar technology with other biomass-management and carbon-drawdown technologies.

2.1. Feedstock

Biochar can be made from a variety of biomass sources including forestry residues, crop residues, purpose-grown crops, manures, and wood reclaimed from municipal waste. Although the most plentiful source of biomass in the PNW is woody biomass from forestry residues (Amonette 2021; Fuchs et al. 2021a), we focus here primarily on crop residues generated on the farm or ranch, due to the focus on biochar production at the small farm scale. Some small agricultural operations may have woodlots to justify biochar production; we will discuss the technology associated with use of this potential feedstock in less detail. We will also make occasional reference to purpose-grown crops such as switchgrass where these provide insights into use of crop residues. Estimates of the sustainable quantities of feedstocks available from these sources are provided in Section 3.1.

The technology associated with biochar feedstock acquisition involves three distinct activities. The biomass must be gathered, processed to an appropriate size and form for the biochar production process being used, and its moisture content adjusted to the level required for optimum production efficiency.

2.1.1. Harvesting

Harvesting methods vary depending on the feedstock. When harvested, cereal and pulse crop residues are generally swathed and baled in a separate operation after the grain is harvested (Tao et al., 2017). Bales are consolidated in a central location awaiting further processing. Old hay bales also constitute a crop residue that may be available in some instances, and these are treated similarly to cereal and pulse crop residues. In addition to baling, bulk handling after swathing and comminution may prove cost effective for switchgrass and other purpose-grown grass biomass crops (REAP-Canada, 2008). Pruning and tree-removal residues from orchard and vineyard operations are transported to a central location for further processing. Depending on the distances involved, chipping or baling of these woody biomass residues can also be done to minimize transportation and handling costs (Johansson et al. 2006; Dooley et al. 2018). Above-ground residues from vegetable crops contain about 5 times more water and 1.8 times more nitrogen (N) than other crop residues (Thiebeau 2021). Because of the additional energy required to dry them they are not economically practical for conversion to biochar. However, their high N content makes them well-suited for use as livestock feed or, in combination with other residues, as feedstock for composting and anaerobic digestion (Cornell University 2022; Gil et al. 2018). Composting or use in digesters presents an opportunity to intersect with other stages of biochar technology (see Section 2.5).

Timing of biomass harvest can also be important. To maximize nutrient retention in soil while minimizing ash and dioxin contents in biochar, a two-stage crop-residue harvesting strategy may make sense in colder climates. Samson and colleagues (REAP-Canada, 2008; Bailey-Stamler & Samson, 2008; Delaquis et al., 2016) recommend mowing and windrowing crop residues in the fall and letting them weather in the field before baling them in the spring. This practice results in leaching of most of the potassium, chloride, and nitrogen from the residues thus avoiding their inclusion in the biochar.

2.1.2.Comminution and Pelletization

Optimal biochar production requires a biomass "particle" size that offers an appropriate surface-to-volume ratio and interparticle void space to achieve the desired rates of heat transfer into the biomass, mass transfer out of the biomass, and adequate gas flow around the particles (Chan et al. 1985; Miller and Bellan, 1996; Gaston et al. 2011; Gauthier et al. 2013; Joseph et al. 2018). This particle size will vary with the biochar production method (Dooley et al. 2021). For flame-cap and slow-pyrolysis batch kilns, biomass particles as large as 4-8" in diameter and lengths of several feet can be used. For auger-feed small gasifiers, smaller uniform particles (1-1.5") are needed. A general rule of thumb is that the heat transfer into a particle during biochar production proceeds at a rate of about 30 mm per hour (0.5 mm per minute). Thus, a 1" (25-mm)-diameter pellet would be completely converted to biochar (and gases) in less than 30 minutes, whereas an 8" (200-mm) diameter log would require several hours. Depending on the feedstock/production method combination, therefore, comminution to make the feedstock smaller (e.g., woody biomass), or pelletization to make it larger or of uniform size (e.g., straw) may be required. Other, pneumatic-feed gasifiers can use straw without pelletization.

Comminution of woody biomass is achieved by cutting to length, splitting larger-diameter boles, grinding, chipping, or crushing (Dooley et al. 2021). Grinders, chippers, and crushers entail significant capital costs that scale with woody biomass-throughput rates. For crop residues, some comminution of straw to shorter lengths may be needed. At least one commercially available gasifier (Qualterra) cuts the straw to 4-inch length and transports it into the gasifier by pneumatic methods.

For finely divided feedstocks (sawdust, straws) used to supply auger-driven gasifier systems, pelletization is needed to provide optimal particle size and shape. This entails additional capital cost, energy (ca. 8-17% of the energy contained in the pellets, Ciolkosz 2009; Chen 2009, p. 34), and associated CO2e emissions (10-20% of the CO2e in the original biomass, Adams et al. 2015; Laschi et al. 2016). However, with some modifications the same pelletization system may prove useful for post-production conversion of the biochar to a form suitable for field application (see Section 2.4). Pelletization also densifies the biomass, which can decrease costs associated with transport and storage space.

A key consideration for pelletization is the mechanical durability of the pellet, which is generally improved by blending feedstocks or by addition of a binder (Piccio et al. 2020, Pradhan et al. 2018; Ciolkosz 2009). For example, when wheat straw or maize stover are blended with wood sawdust, which has a high lignin content, high-quality pellets are produced (Fernandez-Puratich et al. 2017; Stasiak et al. 2017; Azargohar et al. 2018). The need for a binder can often be decreased or eliminated by making briquettes rather than pellets. Aside from size (briquettes being larger and thicker than pellets), briquetting applies higher pressure more efficiently than pelletizing and at a lower capital cost (REAP-Canada, 2008). Switchgrass is another potential biomass source that can be briquetted and pyrolyzed. Samson and co-workers (REAP-Canada 2008; Bailey-Stamler & Samson, 2008) and an economic case study by Penn State Extension (Heil & Ciolkosz, 2014) discuss its potential as a biofuel. Switchgrass also can be used to make biochar (Roberts et al. 2010; Cantrell et al. 2014; Sadaka et al. 2014; Li et al. 2018). Other potential binders, which are typically added at 10 weight percent or less, include crude glycerol (a byproduct of biodiesel production), bentonite, lignosulfonate (a byproduct of wood pulp production), and starch (Piccio et al. 2020; Pradhan et al. 2018). The lignin content of lignosulfonate also enhances the C efficiency of the biochar production process, i.e., the fraction of biomass C that is retained in the biochar (Demirbas, 2001; 2004).

2.1.3. Drying

The optimum moisture content for pelletization is < 20% and, for biochar production, drier is better. When harvested, cereal grains typically contain between 15 and 20% moisture and cereal straws contain 10% moisture or less. At the time of grain harvest, cereal straws, therefore, are already at suitable moisture contents for pelletization and biochar production and should not require further drying. A two-stage harvest approach is recommended by Samson and co-workers (REAP-Canada, 2008; Bailey-Stamler & Samson, 2008, Delaquis et al. 2016) to maximize nutrient retention by soils. This approach leaves the windrowed cereal straw residue from the grain harvest in the fields over the winter to promote leaching of nutrients into the soil. The leached straw residues are then collected in the spring but may require some drying before conversion into biochar and bioenergy.

On the other hand, woody biomass, when harvested or after exposure to weather, may have a moisture content of 50% or higher (Dooley et al., 2018). This content is suitable (indeed preferred) for woody biomass comminution, but not for pelletization or biochar production. Consequently, once comminution has been done, woody biomass may need to be dried. Natural drying of woody biomass with protection from weather will achieve moisture contents of 30% or below but require periods of days to weeks depending on relative humidity and temperature. When time is not available, facilitated drying of woody biomass is needed and this is typically done using waste heat from the biochar production process. With auger-driven gasifiers, drying is achieved as part of the initial heating of the biomass before it enters the pyrolysis chamber.

2.2. Biochar Production

Biochar can be made at multiple scales. We intentionally limit our discussion to scales practical for single farms or local cooperatives, that is, those scales capable of converting 1 to 10 tons of biomass per day. At the average biomass density encountered in the Willamette Valley, these conversion rates service a cropland area of about 3,000 to 30,000 acres. We also focus on production methods with high C efficiencies as these typically have the greatest climate offset potential. Our focus thus excludes fast-pyrolysis systems designed to produce bio-oil and bioenergy with lesser amounts of biochar, as well as air-curtain incinerators and other low-C-efficiency gasifiers.

2.2.1. Flame-Cap Kilns

Flame-cap kilns are moderately shallow open-top containers with sidewalls that typically slope downward towards the kiln center (Pecha et al. 2021; Carloni et al. 2021). Their open-top design facilitates the addition of biomass as large as several feet in length. The kilns are pre-charged with biomass stacked in an open structure and then lit at the top center. Because they are often symmetric (circular, octagonal, hexagonal, or square) in plan view, they provide some beneficial control of the air flow into and out of the biomass being pyrolyzed. Specifically, the flames help create an air circulation pattern that directs incoming air flow to the perimeter inside walls of the kiln while flames located in the top center of the kiln consume much of the particulate matter and volatile compounds such as methane generated by the process. In addition, because the flames radiate heat to the biomass underneath them while consuming most of the oxygen (O_2) that otherwise would cause combustion of that biomass, they promote the pyrolysis reactions that lead to biochar formation.

A typical flame-cap kiln consists of a concave, steel-sided vessel several feet across that is trapezoidal, parabolic, or rectangular in cross section. Portability is important, so smaller kilns may be a single piece, whereas the larger kilns consist of panels that are transported separately and then joined together to yield the kiln. Simpler flame-cap kilns can be made by digging a shallow pit in the ground, but these are less efficient than the steel-lined kilns due to significant losses of heat to the soil that otherwise would promote pyrolysis. They also can sterilize the soil thus aggravating weed control and invasive species concerns.

The greatest advantages of flame-cap kilns are the low capital costs, portability, and great flexibility with respect to biomass form. A variety of designs can be developed to facilitate different biomass forms (Frogner, 2016). With experience and attention to detail, the C efficiency and quality of the biochar produced can be high, particularly for woody biomass. Because they can take feedstock of variable length and diameter, they are well-suited for biochar production from small woodlots. The primary drawback of the flame-cap kiln approach is that they are labor intensive to operate and consequently have more variability in the quality of the biochar produced (Pecha et al. 2021; Carloni et al. 2021; Amonette et al. 2021). Conversion of crop residues requires more frequent attention during operation than does woody biomass due to the smaller diameter of the biomass and enhanced flammability (Frogner, 2016).

2.2.2.Slow-Pyrolysis Kilns

Slow pyrolysis is the traditional method for making biochar (Antal and Gronli, 2003; Garcia-Perez, 2011) but the old methods tend to release significant quantities of methane and soot making them unacceptable from the climate-change mitigation and air-quality perspectives. The chief differences between traditional kilns and modern approaches are biomass handling and clean-up of the emissions. Slow pyrolysis kilns operating in batch mode offer high carbon efficiency (ca. 45%) and when operated under vacuum or with small additions of air can reach dwell temperatures of 600°C or higher.

A prime example of the modern slow-pyrolysis kiln approach is that taken by Biochar Now (Loveland, CO) to handle woody biomass from beetle-killed trees. The biomass is shredded using a special machine to provide the optimal air:fuel ratio and the emissions are cleaned up using a propane-fueled afterburner. The batch production cycle requires at least 24 h to prepare the biomass (about 1 ton), load it into the kiln, ignite the biomass, attach the afterburner/lid, pyrolyze the biomass, cool, and then retrieve the biochar for subsequent processing (crushing and bagging). Each kiln is about 7 feet high and 8 feet in diameter, raised above the ground to avoid soil sterilization issues, and can be transported to different portions of a site for filling with biomass or delivery of biochar. Because of the high capital investment required for specialized biomass and biochar handling equipment, the most economical use of the Biochar Now approach is with groups of 30-60 kilns where continuous usage of the handling equipment is assured, and 15-30 tons of biomass can be processed at a site per day. Nevertheless, a subsidiary of Biochar Now (Mobile Biochar Solutions LLC) has submitted a patent application for a trailer-mounted version suitable for smaller operations that will hold 3 kilns that can swivel to unload biochar without specialized equipment (Gaspard et al. 2022)

It is unlikely that the Biochar Now kiln approach would be practical for crop residues unless they are pressed into pellets or briquets. These would likely need to be metered into the kiln once the initial process has been started and careful control of the introduction of air during the metering process would be required. Some research and development would be required but could prove quite rewarding in the long run.

2.2.3.Small Gasifiers

Strictly speaking, pyrolysis is conducted in the absence of air, but many slow pyrolysis systems introduce a small quantity of air to increase the overall temperature of the process. Because the amount of air added is typically quite small in these systems, they tend to be batch processes. Gasification, on the other hand, is an intermediate process between pyrolysis and combustion wherein some air is available to promote combustion and increase the temperature, but not enough air is added to completely combust the biomass. In the present context, the goal of gasification is to create syngas, a mixture of carbon monoxide and hydrogen (H_2), which can then be combusted to release thermal energy while yielding little or no tar and bio-oil. Flame-cap kilns, for example, combine pyrolysis with limited combustion of the gases generated by gasification. As a result of the introduction of combustion, the carbon efficiency of gasifiers is often less than that of pyrolyzers, but the temperature of the process (ca. 600-800 °C) is considerably higher than that achieved in pure pyrolysis (typically 350-550 °C). The biochar quality produced by gasifiers is high as the higher temperature eliminates most of the volatile matter.

Many of the automated biochar production units available today are hybrids of slow pyrolysis and gasification. They control the amount of air added and burn the syngas to provide heat to dry the incoming feedstock. Carbon efficiencies are comparable to those achieved with slow pyrolysis kilns. In this report we identify them as small gasifiers.

Examples of typical small gasifier systems include the biomass processing units (BPUs) of Qualterra (formerly Ag Energy Solutions, Pullman, WA) and those of Advanced Renewable Technologies International (ARTi, Prairie City, IA). The Qualterra BPUs are designed to work with crop residues, such as wheat straw, although they can also handle woody biomass if milled to pass a ¾-inch mesh. The biomass is transported into the reactor by a pneumatic system. The ARTi units can work with coarse crop residues, such as corn cobs and nut hulls, as well as wood chips, incorporate a syngas-fueled drying stage in their design, and use a twin-auger system to move biomass through the reactor and biochar out of the reactor. Both the Qualterra and ARTi units are engineered to fit into 20-foot shipping containers, making them transportable from site to site with a day or so at each end required to take down and set up. Both units are highly automated and can be operated remotely, thus cutting labor costs. Larger, internally augered gasifier systems are available from ICM, Inc. (Colwich, KS).

Another design that tends to be more robust with respect to maintenance but also engenders higher capital investment, is a rotating kiln. These systems are used in high-throughput facilities and allow great flexibility with respect to O_2 additions, biomass residence time, operating temperatures, and feedstock form. Thus, rotating kilns can operate as pyrolyzers, or low-temperature gasifiers, or even as torrefaction units (heating biomass to temperatures between 200 and 320 °C to dehydrate it, increase energy density, and halt biological degradation for storage purposes). One company in South Dakota (Black Gold Biochar LLC) has a prototype small rotating kiln. Larger rotating kilns are produced by FEECO International (Green Bay, WI).

2.3. Bioenergy Production

Once initiated, pyrolysis is exothermic to a degree (less so as reaction temperature increases, more so as reaction pressure, biomass and vapor residence times, and biochar C efficiency increase, Mok and Antal, 1983; Mok et al. 1992; Spokas et al. 2012; Boateng et al., 2015). Gasification and combustion certainly are exothermic. Production of biochar, thus, necessarily releases energy in the form of heat. Per unit of biomass feedstock, the amount of energy released is inversely proportional to the C efficiency of the biochar production process. Thus, there is a clear trade-off between production of biochar and production of energy, with the decision to optimize one way or the other depending in part on economics and in part on climate-offset goals (Woolf et al. 2010). Beneficial use of this energy (i.e., bioenergy production) can be made, but is rare in smaller systems.

2.3.1. Thermal

Capture of thermal energy generally involves transfer of the heat to a working fluid, which is then used to distribute the heat to where it is needed. Water is the dominant working fluid, but water combined with ethylene or propylene glycol (as in an automobile radiator) is also used where steam is desired. The biochar reactor walls may be lined with tubing through which the working fluid is pumped at a rate that does not draw too much heat from the primary reaction (i.e., maintains overall exothermicity). Alternatively, the exhaust gases pass through a heat exchanger (like air through an automobile radiator) to capture as much heat as possible and cool the exhaust stream. Depending on the heat capture rates, the working fluid may be heated to just below the boiling point or, if electricity generation is desired, steam may be generated, and the complications and higher cost of a pressurized system are encountered.

Once captured, the thermal energy may be used for space heating (as in combined heat and biochar systems), or potentially for other purposes such as enhanced rock weathering (see Section 2.5.3). The dominant use, however, is to dry the feedstock as in the ARTi system. With feedstock drying, the hot gases from the biochar reactor are often used directly to pass over and through the biomass (wood chips) and then back through the high-temperature portion of the reactor.

Mok et al. (1992) report data showing that water in the feedstock helps catalyze biochar formation (relative to other products). Feedstock containing 50% moisture yields about 10% more biochar than that dried to 10% moisture. Of course, more moisture in the feedstock requires more energy to bring it to pyrolysis temperature, but with an excess of energy released as is typical for small biochar systems, this may be of little concern if biochar production is the main priority. Presence of steam during pyrolysis or immediately after pyrolysis also can oxidize the surface of the biochar to produce acidic functional groups as well as to hydrate oxide salts that may be present, thereby decreasing the pH to the neutral range. Additional research is needed to explore how moisture in the feedstock, or added to the reactor, can increase biochar production and alter its properties.

2.3.2. Electrical

In the Pacific Northwest, where cheap hydropower keeps the cost of electricity and the carbon intensity of the grid very low, the expense of an electrical generation capacity is difficult to justify in most circumstances. Remote locations, particularly where electricity is needed temporarily to operate equipment during forest harvesting and thinning operations, offer one exception to this trend. Some remote farms and ranches may also benefit from having permanent, on-site, on-demand, electrical generation capability to complement that generated by solar and wind.

2.4. Soil Amendment

As produced, the physical form of biochar typically reflects that of its feedstock, albeit with substantial shrinkage. The dry biochar may be crushed and passed through a screening process to obtain size fractions ranging from less than 50 mesh (< 300 µm) to as large as an inch (25 mm). A classification scheme like that for soils has been developed to describe the biochar texture (Camps-Arbestain et al. 2015). Most manufacturers offer a fine powder and one or more coarser grades depending on the feedstock. To prevent spontaneous combustion during storage, water is often added to dry biochar after sieving to bring it to 50-150% moisture content. This moisture can affect the handling characteristics of the biochar.

Application of biochar to soils can be done in three physical forms—as a dry powder, as a wet slurry, and as pellets. In addition to these three forms, biochar from woody biomass can be applied as large chunks, depending on the feedstock characteristics. We discuss the benefits and disadvantages of each below.

2.4.1. Powders

All biochar will have some fine powder associated with it due to abrasion from handling and transport. Application of dry powder has been done to the soil surface and subsequently incorporated by disking, harrowing, or other tillage operations. Injection into the subsurface, such as through a no-till drill may work in some instances but caking of the biochar (especially moist biochar) may be a problem. Surface application of dry biochar typically results in airborne particulate matter, which is a significant problem under windy conditions. In general, then, application of dry powder is not recommended unless there is minimal wind, and the biochar is incorporated into the soil soon thereafter.

2.4.2. Slurries

The dry powder can be suspended in an aqueous slurry, which is much more amenable to handling and application in the field. This approach avoids the airborne particulate problem as the biochar suspension tends to enter the soil profile more readily. Perhaps the most common application is injection of a subsurface slurry, often in combination with fertilizer. Banding of biochar offers the grower the maximum value for the biochar (and fertilizer) applied. Broadcast application with irrigation water (e.g., center pivot systems) also has been done successfully. In agricultural systems where water is in short supply, the slurry approach, despite its many benefits, may not be advisable.

2.4.3. Pellets and Chunks

Some of the issues associated with powders and slurries can be avoided by application of biochar either formed into pellets or as chunks (in the instance of some woody biomass biochars). These larger particles avoid the airborne particulate problem and the need for water. Pelletization requires additional infrastructure and energy, although if the biomass is pelletized for biochar production the needed equipment may already be available. Biochar made from pelletized biomass may also retain its pellet form albeit in smaller dimensions due to shrinkage during pyrolysis. Post-production pelletization of biochar, however, offers the opportunity to create a mixture of biochar with other plant nutrients or microbial amendments and may therefore represent a best practice. Exploration of this conceptual space may bear fruit for small agricultural producers.

2.5. Integration with Other Technologies

Biochar technology rarely is a stand-alone operation. It can interface with many other technologies and yield synergies from the standpoint of climate change mitigation. We discuss several of the potential integration options for biochar below, not all of which are practical.

2.5.1. Composting

Incorporation of biochar at 5-10 volume % into green waste- and manure-composting operations has the potential to speed up the composting process and decrease the overall emissions of greenhouse gases during that process. Additional benefits include oxidation of the biochar surface to lower the pH into the neutral range, and the application of nutrients (from the compost). There is some indication that crops may benefit from the application of co-composted biochar more than from biochar and compost alone, though results in the literature have been variable and likely depend on the biochar properties, soil type, and the crop being grown (Fuchs et al. 2021b). Co-composting with biochar is commonly done in California (e.g., Pacific Biochar) and yields a potting mix ingredient for which a premium is paid. The greenhouse gas reduction data in the literature are not universally consistent, however, in part due to the difficulties of getting good emissions data for composting operations. Some work is needed to establish the extent of the climate mitigation benefits for the underlying compost operation.

2.5.2. Greenhouse/Nurseries

Using biochar alone or co-composted biochar as an ingredient in potting mixes for greenhouse and nursery operations is well established and can benefit operations at small as well as large scale. In some instances, waste heat from biochar production is used for winter greenhouse heating and this can provide a significant cost saving as well as a climate offset when replacing propane or natural-gas heating systems. The CO_2 in the exhaust gas may also have some benefit for greenhouse operations, but care must be taken that hazardous gases such as carbon monoxide are not present in the mix. This can be done by filtration or washing the gas with water before injecting it into the greenhouse.

2.5.3. Enhanced Rock Weathering

Weathering of silicate rocks containing calcium and magnesium is the natural process by which CO_2 is removed from the atmosphere. Rainwater in equilibrium with atmospheric CO_2 contains small amounts of carbonic acid, which attacks rocks to release silica along with calcium and magnesium, if present. In the process, carbonic acid is neutralized to form highly soluble bicarbonate ions which percolate through soils into ground and surface waters that eventually reach the ocean. As weathering progresses, the dissolved bicarbonate, calcium, and magnesium ion concentrations in these waters increase until they reach a level where they react to precipitate solid carbonate minerals. Precipitation of calcium and magnesium carbonates in soils and land sediments stores carbon from the atmosphere for decades to millennia; precipitation of these minerals in ocean sediments stores carbon for millions of years.

The rate of rock weathering increases with temperature, the total surface of rock in contact with the acidic water, and the concentration of carbonic acid (which, in turn, increases with the concentration of CO_2 in equilibrium with rainwater). Increasing any of these three factors will enhance rock weathering. As currently practiced, however, enhanced weathering refers to crushing calcium- and magnesium-bearing silicate rocks to increase the total surface available and then spreading this rock on soils to allow the natural weathering process to proceed.

Biochar technology, practices to increase soil organic matter, and enhanced weathering of rocks form a triumvirate of terrestrial carbon-drawdown technologies that have some potentially significant synergies. The synergy between biochar technology and enhanced weathering stems from using the low-grade waste heat from biochar production (after it has lost any steam production value) and the exhaust CO_2 (typically around 15% concentration by volume) to rapidly weather crushed calcium- and magnesium-bearing silicate rocks. After this ex-situ weathering at the site of biochar production, the biochar and the partly weathered rock products can then be spread on agricultural land. In the Pacific Northwest, basalt offers the largest extent of Ca- and Mg-rich silicates that do not also have heavy metal contamination (Ni, Pb, As, etc.) that would prevent land application.

Preliminary geochemical calculations for two representative minerals (diopside and labradorite) found in basalt from Oregon (Amonette, 2022a, 2022b) suggest that any effort involving basalt weathering must take the mineralogical composition into account as shown in a recent paper by Lewis et al. (2021). The effect of temperature is much stronger than that of CO_2 concentration, with as much as a 700-fold difference in rate between 25°C and 90°C. Weathering rates using 15% CO_2 and 90°C are about 5500 times greater for the diopside and 90 times greater for the labradorite than those that would be achieved under ambient conditions. These rates double in going from 15% CO_2 to 100% CO_2, but suggest that for practical purposes, normal exhaust concentrations of CO_2 are adequate. The rate enhancements at 15% CO_2 and 90°C suggest that the equivalent of 15 years of weathering of the diopside could be accomplished in a single day using these waste products. For the labradorite, the equivalent of 3 months of weathering would be achieved.

Use of waste heat and exhaust CO_2 from bioenergy/biochar and other thermal energy facilities to weather basalt rock can significantly expand their climate mitigation potentials well beyond that achieved by a linear combination of energy/biochar production and field weathering under ambient conditions. More research is clearly needed to demonstrate this synergy, but the feasibility seems good at this stage of investigation.

2.5.4. Hydrothermal Carbonization

This process involves treatment of wet organic matter (e.g., food waste) under hydrothermal conditions to form a solid material (often referred to as bio-coal) and an associated liquid effluent that may contain a multitude of organic acids and other compounds. The original appeal of the concept for integration with biochar technology is that the hydrothermal process is exothermic (i.e., it yields heat) and the bio-coal could potentially serve as a feedstock for biochar production, having eliminated the water penalty that is associated with wet feedstocks. However, further investigation of the literature suggests that the capital and operational costs needed to generate the pressures and temperatures of the hydrothermal process would be significant, and that disposal of the liquid effluent could present a problem. Based on this analysis, integration with biochar technology does not seem practical.

2.5.5. Anaerobic Digestion

During anaerobic digestion, wet organic wastes are processed by a community of micro-organisms in an O_2-free (anaerobic) environment. Anaerobic digesters are utilized worldwide in farm settings (as well as in municipal and industrial contexts) to produce bioenergy, reduce odors and pathogens, stabilize waste streams through reduction in solids and organic content, and mitigate greenhouse gas emissions (Abbasi et al. 2012, Costa et al. 2015). Potential integrations of biochar production with anaerobic digestion include biochar production from fibrous digestate that is a product of anaerobic digestion, and/or addition of biochar as a feedstock to anaerobic digestion (e.g., Wambugu 2019). Farm-based anaerobic digesters rely on a consistent (year-round) source of feedstocks to be viable, and often, having at least 500 dairy cows or 2000 hogs are considered minimum “rules of thumb” for economically viable digester implementation, with more favorable conditions as economies of scale are achieved above that (USEPA 2020). Integration of biochar production with anaerobic digestion has been explored. While there are a few examples of digester implementation at small scale in the US, many have struggled to remain economically viable. Thus, integration of biochar production with anaerobic digestion, while a longstanding and still active area of inquiry, may not be as relevant in the small farm context unless as a potential purchaser of biochar.

2.5.6. Small-Scale Farming

Integration of biochar technology with small-scale farm operations has been successfully demonstrated in the developing world where capital resources are limited, and farm labor is relatively plentiful. Synergies include more efficient use of water and fertilizer, safe and sustainable disposal/recycling of organic wastes, and, in many instances, improved crop yields. In the Pacific Northwest, few examples are available, and the primary questions are whether adequate capital can be applied to overcome the limited availability and relatively high expense of farm labor in the US to make these benefits of practical economic value to small farms that often face shortages of both labor and expertise. Yield benefits have been seen inconsistently and even when seen, are not always large enough in value to drive biochar adoption in the absence of carbon incentives. Demonstration of carbon offsets and growth of the value of these offsets are likely to be key factors needed to ensure the success of biochar technology at the small-farm scale. As this report will show, we are optimistic that the climate-offset pathway will lead to economic inputs needed to make this approach successful. However, even if carbon offsets make the application of biochar technology economically viable, additional barriers may need to be overcome. This may include overcoming these farms’ limited access to capital to invest in biochar production technologies. Non-economic barriers, including availability of labor, environmental permitting, and other factors, may be important and should be explored with small farm owners and operators.

3. Potential Climate Impacts

In this section we discuss the size and relative contributions of three major aspects of biochar technology (feedstock resources, energy infrastructure, and soil resources) to its climate offset potential in the Pacific Northwest. Then we introduce the climate-focused life cycle assessment (LCA) approach we will use to help guide our selection of biochar technologies for small-scale agriculture. We conclude by discussing how the different combinations of feedstocks, preparation methods, conversion technologies, bioenergy capture and type, and soil types, as well as the alternative fate of the feedstocks, influence the overall climate impact of biochar technology.

3.1. Feedstock Resources (including Agronomic)

The sustainably harvested biomass feedstocks potentially available for biochar production in the PNW include residues from agriculture and forestry as well as biomass recovered from other waste streams. Of these sources, 37% is from agriculture, 56% from forestry, and 7% from the waste streams (Fig. 4). Within the agricultural sector, about 70% of the biomass is from crop residues, 13% from orchard trimmings, and 17% from manures (Fig. 5). Crop residue production is concentrated in the Palouse and central Columbia Basin of eastern Washington and Oregon, with contributions from the Yakima Valley in central Washington, the Palouse of northern Idaho, the Snake River Plain of eastern Idaho and the Willamette Valley of western Oregon (Fig. 6).

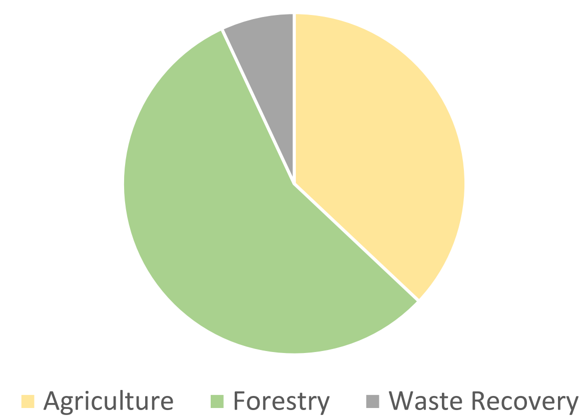


Figure 4. Proportions of sustainably harvested biomass carbon from agriculture, forestry, and waste recovery in the Pacific Northwest ($100/dry ton biomass; USDOE, 2016).

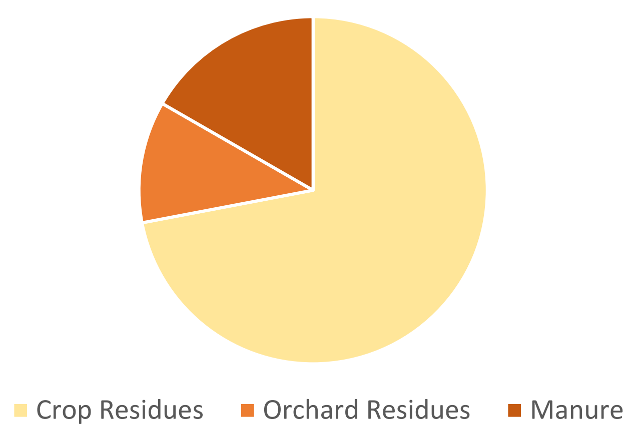


Figure 5. Proportions of sustainably harvested biomass carbon from crop residues, orchard residues, and manure in the Pacific Northwest ($100 dry ton biomass; USDOE, 2016)

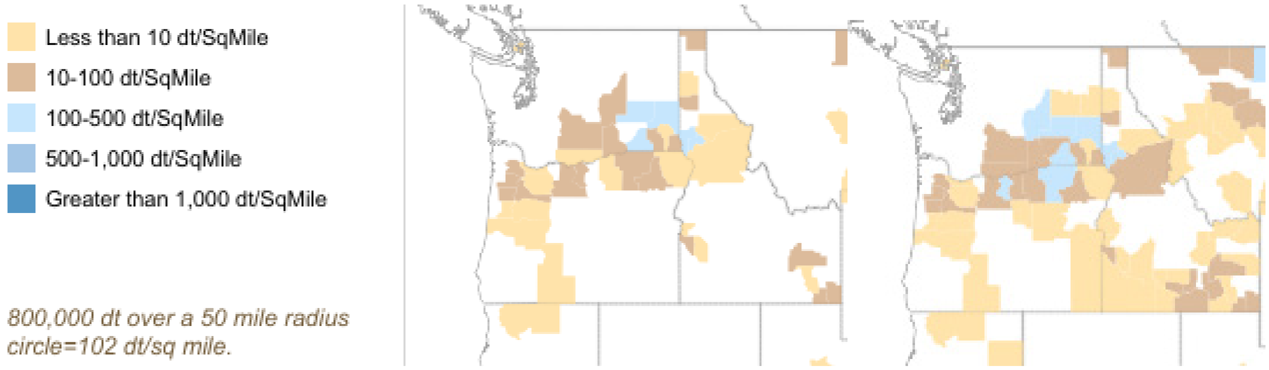


Figure 6. Estimated areal density of annual sustainable crop residue production in the Pacific Northwest in 2022 at $40/dry ton (left) and $80/dry ton (right) (USDOE, 2016).

These estimates of sustainably harvestable carbon in the PNW are summarized in Table 2 in more detail and as a function of biomass price. At the maximum price ($100/dry ton), wheat straw accounts for 66% of the total agricultural carbon available. Agricultural feedstocks can supply about 2.1 million tons of carbon annually. On the forestry side, thinning operations, at 42%, and clear-cut operations, at 39%, account for the great majority of harvestable carbon. Forestry-derived feedstocks can supply about 3.2 million tons of carbon annually. Summing all feedstocks, a maximum of 5.7 million tons of carbon are potentially available on an annual basis for sustainable biochar production.

Table 2. Estimated biomass carbon from sustainable agriculture, forestry, and waste recovery feedstocks in 2022 priced at $50/dry ton or $100/dry ton for the Pacific Northwest (USDOE, 2016)

	Sustainably Harvestable Biomass Carbon, tons C/yr							
	$50/dry ton biomass				$100/dry ton biomass			
Feedstock	WA	OR	ID	Total	WA	OR	ID	Total
Agricultural								
Barley Straw	4,670	1,013	5,412	11,095	12,414	3,334	27,355	43,104
Oat Straw	-	1,914	-	1,914	-	2,287	-	2,287
Wheat Straw	679,510	242,860	226,372	1,148,742	759,859	326,656	321,070	1,407,586
Corn Stover	71,861	-	-	71,861	71,672	-	-	71,672
Miscanthus	-	-	-	-	327	-	-	327
Orchard Trimmings	194,213	29,968	3,435	227,616	194,213	29,968	3,435	227,616
Tree Nut Shells	108	12,277	0	12,385	108	12,277	0	12,385
Dairy Manure	92,851	38,214	222,087	353,152	92,851	38,214	222,087	353,152
Forestry								
Natural Logging Residues	-	-	-	-	293,939	-	-	293,939
Natural Thinning Operations	-	-	-	-	417,145	-	16,242	433,388
Natural Clear Cut Operations	-	-	-	-	1,257,399	-	-	1,257,399
Plantation Logging Residues	-	-	-	-	1,587	-	-	1,587
Plantation Thinning Operations	-	-	-	-	699,102	219,619	-	918,721
Plantation Clear Cut Operations	-	-	-	-	226,695	70,501	-	297,197
Waste Recovery								
Mill Residues	53,141	-	-	53,141	53,141	69,915	18,231	141,288
MSW Wood	72,227	12,383	2,141	86,750	72,227	40,832	16,711	129,769
Yard Trimmings	39,294	6,737	-	46,031	39,294	22,214	1,165	62,673
Food Waste	-	-	-	-	52,343	8,974	1,552	62,868
Total Agricultural	1,043,212	326,247	457,307	1,826,766	1,131,445	412,737	573,947	2,118,129
Total Forestry	-	-	-	-	2,895,867	290,121	16,242	3,202,230
Total Waste Recovery	164,662	19,119	2,141	185,922	217,004	141,935	37,659	396,598
TOTAL Available Biomass Carbon	1,207,874	345,366	459,448	2,012,689	4,244,316	844,793	627,848	5,716,958

3.2. Energy Infrastructure

Biochar production releases energy directly in the form of heat. The products of pyrolysis, including tars and condensable gases that lead to bio-oil (primarily from fast-pyrolysis systems), syngas (a mixture of hydrogen and carbon monoxide), and biochar itself, store energy that can later be released by combustion. However, the biochar technologies considered in this report combust the tars and syngas as part of the biochar production process, thus adding to the heat released during pyrolysis. This heat can be used to generate electricity, and the lower grade heat remaining used to dry feedstock, for space-heating, or for other purposes, such as enhanced weathering of silicate rocks.

The climate impact of capturing and using the energy released during biochar production depends on the carbon intensity of the energy that it replaces. The carbon intensity of common fossil fuels used for heating, such as natural gas and fuel oil, is greater than 50 kg CO2e / GJ (Table 3). Because of the abundant hydroelectric power available, the carbon intensity of the primary energy supply in the PNW is between 30 and 40 kg CO2e / GJ, 15% to 30% smaller than the US average of 47 kg CO2e / GJ. The dominance of hydropower in the electricity market of the PNW yields carbon intensities that are only 27% to 38% of the national average for electrical power. Consequently, the net volume of carbon credits for replacing grid electricity with that generated during biochar production will be substantially less than elsewhere in the USA. Because baseload hydroelectric plants are unlikely to be displaced by additional energy generation, it may be more prudent to compare the carbon intensity of bioenergy production to the next marginal resource on the grid, typically natural gas in the PNW.

Table 3. Carbon intensities of the primary energy supply and of electricity in the Pacific Northwest and in the United States in 2020 (US Energy Information Administration, 2022).

Energy Sector	State			USA
	WA	OR	ID	Average
Primary Energy Supply	-------------------- kg CO2e/GJ --------------------			
	31.8	33.4	39.3	46.9
	----------- Fraction of USA Average, % -----------			
	68%	71%	84%	--
Electricity Production	-------------------- kg CO2e/MWh --------------------			
	103	147	125	387
	-------------------- kg CO2e/GJe --------------------			
	28.6	40.8	34.8	107
	----------- Fraction of USA Average, % -----------			
	27%	38%	32%	--
Fossil Fuels	-------------------- kg CO2e/GJ --------------------			
Natural Gas (Residential)	50.3	50.3	50.3	50.3
#2 Distillate Fuel Oil (Refiner's Retail)	70.1	70.1	70.1	70.1

Smaller net carbon credits are reflected in the economics as well. To illustrate this, the retail values of electricity, natural gas, and fuel oil in the PNW and for the USA average are compared with the nominal values of the carbon credits that could be earned from biochar production assuming $100 / tonne CO2e (Table 4). This comparison shows that the carbon credits from biochar electricity production in the PNW would be only 12% to 17% of the value of the electricity (less than half those for the USA average). Thus, generation of bioelectricity for the electric grid would probably not be economical after accounting for expected higher costs of production relative to hydropower. Generation of bioelectricity might prove economical for temporary, remote, off-grid sites where the cost of connecting to the grid is high and is often suggested for operation of biomass processing equipment at forest landings. Replacement of natural gas or fuel oil using heat generated by biochar production, however, nets a 45% to 70% premium that is comparable to or better than that expected for the US on average. Use of this heat to generate additional carbon-credit premiums from enhanced weathering of Ca, Mg, and Fe-bearing silicates might prove economic in some situations, given the abundance of these rocks in the PNW.

Table 4. Retail value of electricity, natural gas, and fuel oil per unit of energy, the value of carbon credits if this energy is replaced by bioenergy from biochar production, and the premium offered by the carbon credits relative to the market price of the energy being replaced.

Energy Sector	State			USA
	WA	OR	ID	Average
Retail Value of Energy	------------------------ $/GJ ------------------------			
Electricity	23.14	24.50	22.19	29.42
Natural Gas (Residential)	10.89	10.88	6.85	11.54
#2 Distillate Fuel Oil (Refiner's Retail)	11.36	11.36	9.90	11.36
Retail Value of Carbon Credits ($100/t CO2e)	------------------------ $/GJ ------------------------			
Electricity	2.86	4.08	3.48	10.75
Natural Gas (Residential)	5.03	5.03	5.03	5.03
#2 Distillate Fuel Oil (Refiner's Retail)	7.01	7.01	7.01	7.01
Carbon Credit Premium	----------- Fraction of Energy Value, % -----------			
Electricity	12%	17%	16%	37%
Natural Gas (Residential)	46%	46%	73%	44%
#2 Distillate Fuel Oil (Refiner's Retail)	62%	62%	71%	62%

3.3. Soil Resources (including Agronomic)

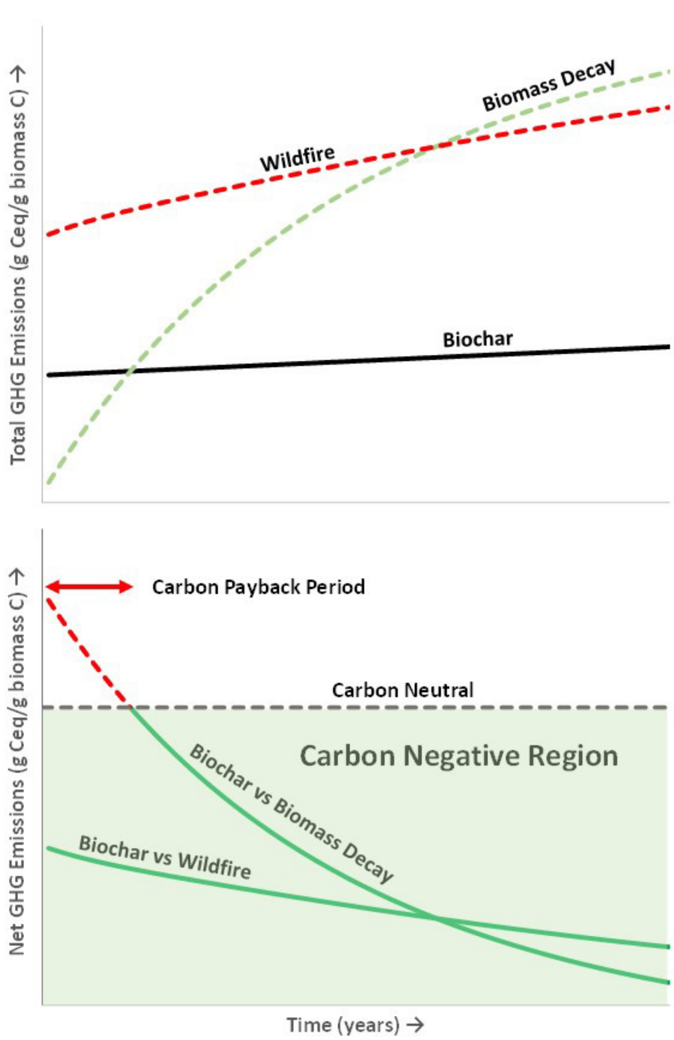
The availability of soils as a storage medium for biochar and their responses to biochar amendments will vary significantly with soil properties and will also dictate what types of biochar can be productively incorporated. Acidic soils, for example, will benefit from the liming effect of alkaline biochar straight from the production line, whereas alkaline soils will need that biochar to be treated (e.g., by co-composting) to decrease its pH to the neutral or even acid region before incorporation. These soil properties are available in Geographical Information System (GIS) form from the USDA-NRCS Soil Survey online database (SSURGO) that allows them to be mapped to identify where different biochars are best applied. The SSURGO database also provides information about pre-existing soil-C stocks, which serve as a key factor for predicting the potential of biochar amendments to stimulate non-pyrogenic soil organic matter (npSOM) accumulation in soils (Amonette, 2021). Soils with high pre-existing soil carbon stocks are more likely to encourage additional npSOM accumulation when biochar is applied because their environmental factors already suggest that npSOM is more stable.

Agronomic soils, because of the ease of mechanical incorporation of biochar, offer the best location for its storage. It can be surface applied to rangeland and forested soils, but likely requires pelletization to minimize airborne dust and allow slower incorporation by natural perturbation processes like those that operate with charcoal from wildfires. Estimates of the total arable land available in the Pacific Northwest for biochar suggest that many decades of biochar storage capacity are available before applications to rangeland and forest soils, and storage in other sinks need to be developed (Amonette, 2021).

3.4. Time-sensitive Life Cycle Assessment

The concept of a time-sensitive LCA is described by Amonette et al. (2021):

“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 [Cowie et al. 2015; Roberts et al. 2010; Sahoo et al. 2021].



Because the impact of GHGs changes with time due to their different atmospheric residence times relative to CO_2, the climate impact will also change depending on the period being considered. A time-sensitive LCA approach fully captures this dynamic as shown in a hypothetical example for biochar and two alternative biomass fates (Figure 7). 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."

Figure 7. Two stages in a hypothetical time-sensitive LCA of biochar technology. (Top) Total GHG/A emissions of biochar and two alternative fates of the same woody biomass feedstock (decay in place and wildfire). (Bottom) Net GHG/A emissions of the biochar approach relative to biomass decay and to wildfire. The C-payback period is the period during which biochar technology has higher cumulative GHG/A emissions than the biomass-decay option.

The overall climate-mitigation impact is thus tied strongly to the sustainability of the biomass harvesting practices, the efficiency of the biochar production process, and the alternative pathways by which C from the biomass returns to the atmosphere. When biochar is made from biomass waste byproducts – such as cereal straws, orchard and vineyard prunings, food-processing waste such as fruit and nut pits and shells, lumber mill wastes, forest management byproducts, defensible space clearing (for wildfire risk reduction), urban or suburban yard wastes, and even livestock manure—the utilization for energy and biochar can be C negative (Figure 7). Compared to baseline disposal through natural on-site decay, composting, on-site open burning, or spreading of wood chips, production of biochar and bioenergy by modern low-emission facilities yields significant climate benefits by avoidance of: (a) the combustion of fossil fuels for comparable energy production, (b) significant immediate release of CO_2 as would occur by processes having low C efficiency, and (c) the disposal of the biomass wastes by methods that may release significant amounts of CH_4 or soot.

3.5. Biochar Technology Implementation

We consider biochar technology in terms of three stages: *pre-conversion*, in which the biomass is harvested, transported, and prepared for biochar production, *conversion*, in which the biomass undergoes thermochemical treatments to create biochar and release energy, and *post-conversion*, in which the biochar is transported and incorporated into soil (often after co-composting) where it has a variety of impacts on climate-relevant soil properties and processes as it slowly decays. Each of these stages has its own group of technological pathways from which to choose. Actions during each stage can increase the CO2e level in the atmosphere and, for the conversion and post-conversion stages, decrease the CO2e level in the atmosphere. The sum of the CO2e increases and decreases stemming from these actions yields the overall climate impact of a specific implementation of biochar technology. In this section, we develop an example that shows the relative climate impacts of each action and how these combine to yield a range of climate impacts for different implementations of biochar technology. Comparison of the fate of the biomass C used for biochar with alternative uses of the same C helps guide selection of the optimal group of technologies for implementation.

We start by listing the major factors contributing to climate impacts from actions at each stage of biochar technology (Fig. 8). The relative potential climate impact of each factor is given by the height of the box, with atmospheric CO2e increases shown in light red and atmospheric CO2e decreases shown in light green. For the pre-conversion stage the major factors are biomass harvest, transport, comminution/pelletization, and drying, each of which increase CO2e levels. For the conversion stage, emissions of greenhouse gases and aerosols (GHG/A), which are associated with the C efficiency of the process, potentially dominate the climate impacts. Consumption of energy (e.g., grid electricity or propane to initiate pyrolysis) may contribute to a small extent. Capture and beneficial use of the energy released during conversion (either as electricity or simply as thermal energy) can decrease CO2e levels significantly by avoiding combustion of fossil fuels as can the use of waste heat and CO_2 to enhance weathering of Ca- and Mg-rich rocks (e.g., basalt, serpentinite). In the post-conversion stage, many relatively modest impacts are seen with co-composting and soil incorporation of biochar leading to potential decreases in CO2e levels stimulated by formation of soil organic matter and by enhanced plant productivity. These potential CO2e decreases are balanced by potential CO2e increases from transport and tillage to incorporate biochar, slow decay of the biochar in soil, and the possible (rare) stimulation of npSOM oxidation by biochar amendments. The sum of all the potential CO2e increases and decreases, which are taken here at their maximal value (highly unlikely in any given scenario), yields a net CO2e balance of 28 units indicating net release of CO2e to the atmosphere relative to the original biomass C without any processing or decay. In fact, as will be shown in the specific examples that follow, the LCA will compare these CO2e balances for a given implementation of biochar technology with those for an alternative pathway for the same biomass C to achieve a wide range of net climate impacts that include increases and decreases of atmospheric CO2e levels.

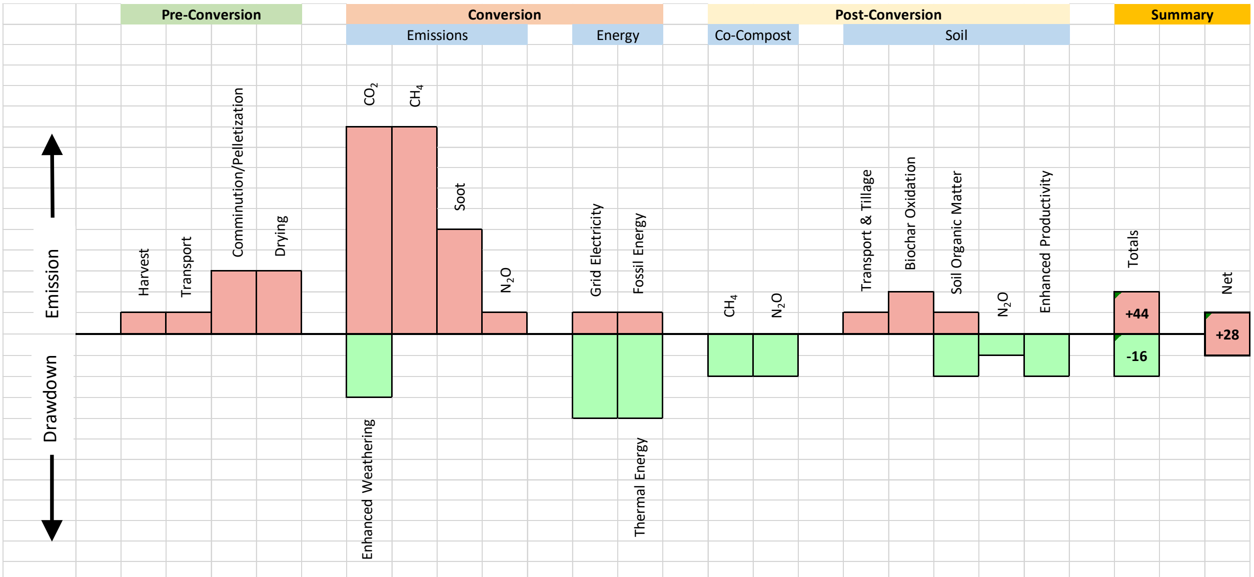


Figure 8. Relative potential climate impacts of actions during the three stages of biochar technology. Height of box for each factor shows potential relative CO2e impact; relevant impacts for this scenario are colored to indicate CO2e emission (light red) or drawdown (light green). All values are qualitative and for illustrative purposes only.

For this LCA example, we have selected straw from crop production as the feedstock, and two biomass alternative pathways, decay in soil, or composting followed by decay in soil. The second of these pathways is shown in Fig. 9, where the CO2e increases during the composting and decay are given under the conversion stage. Some decreases in CO2e levels may be achieved from increases in soil organic matter and productivity when this biomass is added to soil. The net CO2e balance is +14 units for this alternative.

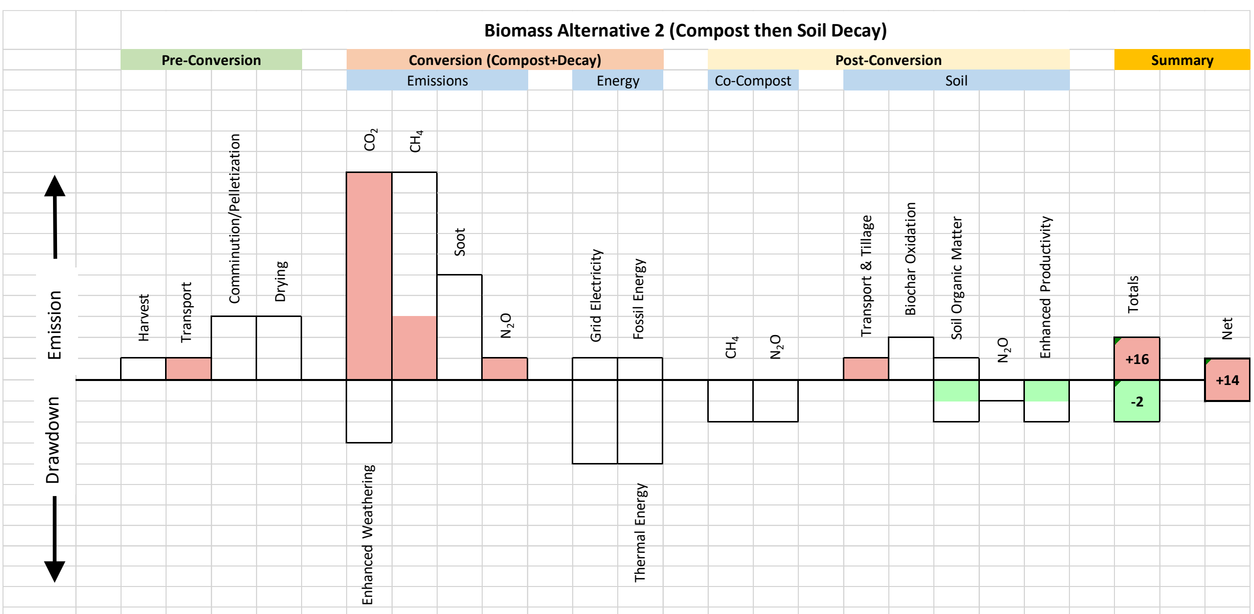


Figure 9. Major factors in LCA of biomass alternative fate assuming straw biomass is composted and then incorporated into soil where it decays rapidly. Height of box for each factor shows potential relative CO2e impact; relevant impacts for this scenario are colored to indicate CO2e emission (light red) or drawdown (light green). All values are qualitative and for illustrative purposes only.

One of the biochar technology implementations considered includes high C efficiency, capture and use of the energy released to offset fossil CO2e that might be emitted to provide thermal energy, production of high-quality biochar (high stability of the biochar C towards decomposition in soil), co-composting of the biochar, and maximum CO2e removal from the atmosphere due to stimulation of soil organic matter accumulation and plant productivity while decreasing N_2O emissions. The net CO2e balance for this implementation is +1 unit (Fig. 10).

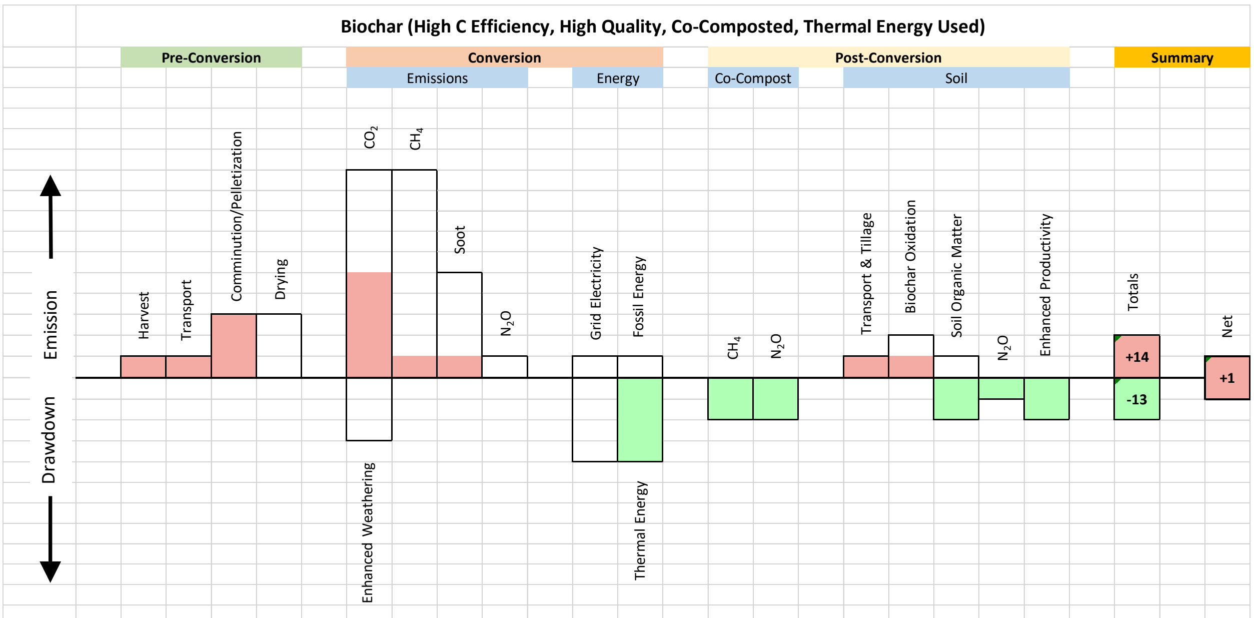


Figure 10. Major factors in LCA of high-quality biochar prepared from straw biomass with high C efficiency and use of thermal energy to offset fossil-C emissions. The biochar is subsequently co-composted and then incorporated into soil where it decays very slowly. Height of box for each factor shows potential relative CO2e impact; relevant impacts for this scenario are colored to indicate CO2e emission (light red) or drawdown (light green). All values are qualitative and for illustrative purposes only.

The specific factors included for 9 implementations of biochar technology and the two alternative biomass pathways are listed in Table 5 along with the absolute CO2e balance for each, and the net CO2e given by the LCA which is the difference between the absolute CO2e balances for each pairing of biochar technology and alternative biomass pathway. These clearly show that biochar implementations that emphasize C efficiency, biochar quality and co-composting combined with the enhancements to soil properties and processes yield the best overall climate impacts. The degree to which each of these actions are implemented will depend on the balance between the economics of their implementation (i.e., their cost and the availability of carbon credits to pay for their implementation).

Table 5. Summary of hypothetical LCA results for nine biochar production scenarios relative to two alternative biomass fates. Values for atmospheric CO2e increase (light red) and decrease (light green) are qualitative and for illustration purposes only. Substitution of cut straw for pellets is assumed to decrease CO2e emissions for comminution/pelletization during the pre-conversion stage from three units to one unit.

Scenario	Feedstock	Conversion Path									Qualitative C Emissions				
											Pellets			Cut Straw	
	Straw	Compost	Decay	Pellets	C Efficiency	Biochar Quality	Co-Compost	Electricity Generated	Thermal Energy Used	Enhanced Weathering	Absolute	LCA Net Altern 1	LCA Net Altern 2	LCA Net Altern 1	LCA Net Altern 2
Biomass Alt_1	X	--	X	--	--	--	--	--	--	--	10	--	--	--	--
Biomass Alt_2	X	X	X	--	--	--	--	--	--	--	14	--	--	--	--
Biochar_1	X	--	--	Yes	Low	Low	No	No	No	No	15	5	1	3	-1
Biochar_2	X	--	--	Yes	Low	High	No	No	No	No	12	2	-2	0	-4
Biochar_3	X	--	--	Yes	High	High	No	No	No	No	9	-1	-5	-3	-7
Biochar_4	X	--	--	Yes	High	High	Yes	No	No	No	5	-5	-9	-7	-11
Biochar_5	X	--	--	Yes	High	High	Yes	No	Yes	No	1	-9	-13	-11	-15
Biochar_6	X	--	--	Yes	High	High	Yes	Yes	No	Yes	-1	-11	-15	-13	-17
Biochar_7	X	--	--	Yes	High	High	Yes	No	Yes	Yes	-2	-12	-16	-14	-18
Biochar_8	X	--	--	Yes	High	High	Yes	Yes	Yes	No	-3	-13	-17	-15	-19
Biochar_9	X	--	--	Yes	High	High	Yes	Yes	Yes	Yes	-6	-16	-20	-18	-22

3.6. Other Environmental Impacts

Agricultural residues may contain significant levels of chloride (Cl), which can combine with aromatic C entities to produce highly toxic dioxins under certain conditions. In general, dioxins are not a major concern with most biochar production approaches and can be avoided by operating at high temperatures (600 °C or higher) and minimizing the contact of pyrolysis gases with cooler (ca. 300-400 °C) aromatic C solids. As stated by Garcia-Perez and Metcalf (2008, p. 15), "Systems ensuring high temperatures and long vapor residence times in the furnace as well as fast cooling of combustion products are likely to achieve low emissions of PCDD/F even while using feedstocks with large contents of chlorine."

Another potential class of contaminants is the polycyclic aromatic hydrocarbons (PAHs), of which biochar may be considered an extreme example. In fact, it is molecules consisting of small clusters of aromatic hydrocarbon rings (ranging from two to a dozen or so) that are hazardous. These clusters are generally destroyed under the conditions encountered in modern pyrolysis/gasification reactors but can accumulate on the surfaces of biochars where colder zones are found in the reactor (Buss et al. 2022). Thus, PAHs are of most concern in situations such as flame cap kilns where operator actions can affect the consistency of biochar production. Even when produced, however, strong sorption of PAHs to biochar surfaces suggests that these compounds generally pose little threat (Garcia-Perez and Metcalf, 2008; Granatstein et al. 2009; Hale et al. 2012; Keiluweit et al. 2012; Bucheli et al. 2015).

During comminution, pelletization, drying, and storage of biomass, volatile organic compounds (VOCs) are released and, while they generally decrease climate impact, they do contribute to the production of ozone, particulate matter (PM2.5), and smog and thus are atmospheric pollutants (Williams and Koppmann, 2007; Reimann and Lewis, 2007). Pre-conversion processing of biomass, therefore, should include measures to minimize the release of VOCs to the atmosphere, and storage of biomass prior to conversion should be minimized. An ideal situation might be location of the pre-conversion processing operations at the site of biochar production thus allowing capture of the VOCs and their introduction into the air intake of the biochar production facility where they can be destroyed.

4. Carbon Offset Funding Mechanisms

In this section we introduce carbon offset crediting, discuss two carbon crediting mechanisms for biochar in some detail, explore some of the technical gaps that affect pricing/quality of biochar carbon credits and then briefly discuss carbon credits associated with applications of biochar technology to other carbon offset technologies. We conclude by discussing the potential revenue streams for biochar carbon credits now and in the future.

4.1. Overview of Carbon Offset Crediting

Carbon offsets are generated from activities that avoid or remove greenhouse gas emissions. Eligible activities are determined by independent carbon registries as part of voluntary or compliance carbon markets. Carbon registries establish the rules - referred to as Methodologies or Protocols - that govern project documentation, credit quantification, and project verification. Methodologies determine how projects meet fundamental carbon quality standards, including *additionality* (activities must exceed legal requirements/compliance obligations and go beyond standard practices), *permanence* (activities must maintain emissions reductions or drawdown for a given duration), *measurability* (activities must provide evidence that real emissions reductions have occurred), *transparency*, and *verifiability* (typically by an accredited third party). A workable, scientifically credible biochar methodology that is recognized by established carbon buyers represents critical market infrastructure for scaling biochar carbon offset project development.

Methodologies are typically developed through internal registry processes or through initiatives proposed by project developers and other stakeholder groups. In either case, registries tend to convene technical and/or industry working groups that provide guidance around how a proposed project type would conform with registry standards. When a methodology's language is drafted and released publicly, it typically is reviewed through a public comment period and amended as necessary. For some registries, proposed methodologies are also reviewed by a verification body. With Verra, for example, proposed rules are reviewed by two independent verifiers before formal adoption by the registry. The process of writing and adopting a new methodology can take 1-5 years, depending on the level of public comments, the familiarity of the registry with the project area, sources and magnitude of uncertainty, the potential volume of credits a protocol is projected to generate, and the extent to which staff time may be covered by industry sponsors. Protocols can cost between $200k-$500k to develop, not including the time investment of stakeholders involved in the process.

Registries also allow for the revision of protocols over time. This can include marginal updates of language to create more clarity, approving new monitoring tools or approaches, or clarifying eligibility and technical gaps identified through initial project development under a new methodology. Revising a methodology can take less time and resources than starting from scratch, though it can still take 12-18 months and is subject to the priorities of the registry.

4.2. Current and Proposed Mechanisms

There are four established nonprofit registries that account for the majority of voluntary carbon offsets - Verra, Gold Standard, Climate Action Registry (CAR), and American Carbon Registry (ACR). These registries conform to similar quality standards surrounding Additionality, Measurability, Permanence, Transparency, and Verifiability, and have methodologies that are recognized in both voluntary contexts and many compliance markets such as California's state-based carbon market and CORSIA, the Carbon program established by the International Civil Aviation Organization (a division of the United Nations). These registries all have public protocol development processes that include some level of public comment, scientific review, and stakeholder engagement. These registries account for almost 1.5 billion tons of credits since 1998. In addition to these traditional registries, there has been a proliferation of alternative for-profit registries, including Nori, Indigo, NCX, and puro.earth, that have provided alternative marketplaces and new methodologies to support project development.

While several traditional registries have publicly indicated their interest in developing a biochar protocol, none have active protocols against which a developer may register a project. ACR drafted a biochar protocol in 2013 that eventually was shelved due to concerns around biochar stability and quality standards (see more on Technical Gaps in Section 4.3). Verra released a draft protocol in April 2021, developed by Biochar Works, Forliance, and South Pole, but as of July 2022 the methodology is still listed as "under development," despite public comments closing in September of 2021. CAR also has plans to release a biochar protocol and convened a technical working group to assist their development. Communication with CAR staff in early 2022 indicated that the methodology development process was delayed due to capacity constraints.

4.2.1. Verra

Verra's methodology appears to be closest to market ready among the traditional registries. Verra allows for a range of technologies from lower tech (kilns, mounds) to high tech gasifiers and pyrolizers. The methodology includes conservative default emissions values and carbon conversion efficiencies for lower tech solutions, and the ability to put forward well researched numbers for higher tech solutions. The greenhouse gas boundary includes sourcing, transporting, and processing of biomass, and biochar production and application. Carbon credit quantification is primarily influenced by the quantity produced and carbon content of the biochar. A decay rate is also applied to account for the degradation of bioavailable carbon in the biochar. The permanence period for biochar carbon projects is 100 years, thus the decay rates determine how much of the initial biochar carbon content will remain after 100 years, based on modeled rates of decay. The carbon credit calculation also factors in any deductions for emissions generated in the process of operating the production facility. Credits are calculated in units of tonnes of CO_2 equivalent (CO2e).

The default baseline emissions scenario for biomass feedstocks is considered 0, though projects can substantiate a positive baseline with additional evidence. In order to establish an alternative baseline, projects must assemble three years of records and studies pertaining to the specific feedstock. Alternative scenarios may only consider decomposition or burning of biomass in calculating a baseline. When sourcing biomass from agricultural operations, Verra requires projects to leave at least 30% of crop residues to prevent degradation of existing carbon stocks. We note that the amount of crop residues needed to prevent soil degradation is context dependent and may be higher than 30% in semi-arid cropping systems of the Pacific Northwest (Machado 2011, Tao et al. 2017).

Projects must document that all biochar has been utilized and applied in an eligible soil or permanent non-soil application. For non-soil applications, projects must demonstrate in peer-reviewed literature that the end use represents a long-lived and durable carbon sink. Biochar may not be used for "energy purposes" though there are limited exceptions for cogeneration applications and facilities with limited fossil fuel use that preserve greater than 50% of original biochar material. For soil applications, biochar must meet International Biochar Initiative standards and testing to ensure no heavy metals or other contaminants get transferred to soils. The application method determines the biochar permanence factor, which discounts the amount of credits a project can claim. The default permanence factor for soil applications over 100 years is 0.74, meaning that 74% of the carbon in the original biochar remains after a century. Projects may determine an alternative permanence factor with support from scientific literature. The permanence factor in soil is considered conservative, and alternative use cases, such as storage in cement, may either utilize the soil default or submit research that establishes higher permanence factors. In the Willamette

Valley, based on average soil temperatures (Bates, 1975), the expected permanence factor ranges from 0.72 to 0.91 (depending on the biochar quality measured by the atomic ratio of H/C_{org}) over 100 years (based on Woolf et al. 2021 and references cited therein).

4.2.2. Puro.Earth

An upstart registry in Finland called Puro.Earth launched in 2018 was the first to create a marketable biochar methodology. Their methodology requires similar standards of additionality and verification to conventional registries but emphasizes project permanence and carbon removal as a differentiator relative to other marketplaces. They also require each project to perform a full Life Cycle Assessment as a prerequisite to project registration. The methodology requires incorporating a more expansive set of variables than Verra, including emissions associated with the production and disposal of equipment used to produce biochar, as well as emissions from land use changes resulting from biochar projects. The decay rates in soil are also determined by the local average soil temperature where biochar is being applied. The methodology is otherwise very similar to Verra's draft methodology, including its default assumption of zero baseline emissions, and the ability to substantiate a positive baseline.

As of May 2021, 66,000 tons of CO2 Removal Certificates (CORCs) from biochar projects had been registered with Puro.earth. Microsoft purchased 1,900 tons of credits from Puro.earth in 2020, at a "significant premium" relative to shorter duration carbon projects. In 2021, Microsoft increased their purchases to more than 11,000 tons from six different projects, including Pacific Biochar, which produces biochar from agricultural residues.

In 2021, NASDAQ bought a controlling interest in Puro.Earth, which they have leveraged to bring further price transparency to carbon removal projects. They have pegged a CO2 Removal Certificate Reference Weighted Index to Puro.Earth projects including biochar projects. As of April 2022, the biochar index was greater than $108 per ton. Pricing at this rate for medium-to-long duration carbon projects was corroborated in conversations with two other carbon brokerages with exposure to a wide range of carbon offset project types.

The strong carbon pricing from Puro.Earth projects is encouraging for biochar development but does not necessarily predict prevailing prices as the industry matures. Procurement initiatives like that of Frontier's nearly $1 billion carbon removal commitment are meant to help technologies get down the cost curve and reduce pricing for the sector. As a "medium-duration" carbon removal solution, it is unclear if Biochar will maintain its attractive pricing relative to long duration technologies like Direct Air Capture and Enhanced Weathering when they come to market at scale. When modeling projected revenues from carbon markets in this feasibility phase, it is prudent to be conservative, while recognizing that biochar likely will outperform conventional carbon offset pricing, given its potential for more permanent carbon storage. It is highly recommended that early-stage biochar projects explore multi-year carbon offtake agreements where possible to help hedge some risk of market volatility.

4.3. Technical Gaps

Efforts to establish biochar methodologies and develop projects have been undermined by a perceived lack of scientific consensus on the stability and quality of biochar. In the last decade, many of these challenges have been vetted in the scientific literature and addressed by standards organizations, but some uncertainty around the permanence of benefits and the performance across various production technologies and biochar applications introduces costs and uncertainties to project development.

In 2013, the American Carbon Registry developed a draft methodology that never was officially adopted by the registry. The public comments and peer review documents indicated uncertainty surrounding the stability of carbon contained in biochar and how quality would be monitored. A subsequent literature review (Fawzy et al. 2021) provides evidence from several studies that utilized exponential decay modeling of carbon isotopes to establish the mean residence time of biochar carbon (Wang et al. 2016) and developed proxies for biochar stability using molar ratios of H or O to organic carbon (C_{org}, Spokas 2010; Wang et al. 2013; Lehmann et al. 2015). These studies helped clarify that more than 97% of biochar is not bioavailable and thus resistant to degradation. Biochar with a molar ratio of O to C_{org} (in the original feedstock) of 0.2 has a 1000-year half-life (Spokas 2010). Similarly, a molar ratio of H to C_{org} (H / C_{org}) in the biochar of less than 0.4 implies a biochar half-life of 870 years (Lehmann et al. 2015). This research informed the standards for the European Biochar Certificate, which requires an $O:C_{org}$ ratio of 0.4. The EBC, a standard Puro.Earth's methodology requires projects to meet, also addressed concerns of quality monitoring, by establishing independent sampling protocol and accreditation requirements for labs.

Conversations with CAR staff revealed persistent technological gaps in the quantification of carbon credits generated from biochar production. Because of the variability of biochar production techniques and how produced biochar is utilized, there was a desire for better models or proxies that could help projects assess and monitor the performance of various technologies and approaches. More published data about expected carbon conversion ratios for various feedstocks and emissions profiles for different production techniques and processing tools could help inform tools provided within a methodology to estimate carbon crediting. These tools can help simplify verification and monitoring processes and reduce the uncertainty of project development. With limited data, registries will either use conservative proxies or require projects to undertake expensive monitoring that may erode the economic value of a project.

Another important technical gap and source of unrealized value in carbon markets, is a lack of tools that accurately model the priming effect of biochar. Priming refers to the changes in npSOM that materialize after biochar is applied to agricultural soils. Because of biochar's ability over the long term to retain and protect organic carbon that otherwise would be leached from the soil or consumed by soil microbes, it can lead to an increase in stocks of npSOM (Woolf and Lehmann, 2012; Maestrini et al. 2014; Borchard et al. 2014; Hernandez-Soriano et al., 2016; Kerre et al. 2016; Wang et al. 2016; Weng et al. 2017; Blanco-Canqui et al. 2019).

To help fill this gap, Amonette (2021) developed an algorithm consistent with the available evidence and applied it to biochar production in Washington State. At maximum biochar production levels, the npSOM content of Washington agronomic topsoil was predicted to increase 3-fold from 115 Mt of carbon to 340 Mt of carbon over the course of a century. When parsed in terms of the biochar, the algorithm predicts that addition of 3 tons of biochar to agronomic soils would stimulate the accumulation of between 1 and 2 tons of carbon in the form of npSOM. To confirm these predictions, long term studies that capture delayed biochar benefits and isolate the conditions that stimulate npSOM accumulation can help ensure biochar impacts are maximized. Ultimately, improvements to and confirmation of modeling tools based on these long-term field trials will allow registries to incorporate priming impacts into the calculation of a carbon credit, further incentivizing collaboration between biochar producers and farms where biochar may be applied.

4.4. Cross-Technology Logistics

As discussed in section 2, biochar systems may have the potential to augment other technologies with positive climate impacts and potential applications in carbon crediting programs. Integrations with feed additives, soil carbon projects, and enhanced weathering technologies may provide added synergies in carbon markets.

Applying biochar to feed additives may represent a pathway for additional methane reduction and carbon crediting. There is some evidence that biochar additions to cattle feed may reduce methane from enteric fermentation by 12.7%. Subsequent study has indicated those lab scale results may not be replicated in feedlots (Graves et al. 2022; Mengistu et al. 2022). If those benefits do materialize, there are available methodologies from Gold Standard and Verra whereby further crediting may be generated.

While biochar serves a long-term role in boosting microbial activity and soil organic carbon in soils, Verra's methodology does not allow projects to receive additional credits for "priming" carbon sequestration in soil. Though biochar application is not specifically called out as a practice eligible for crediting in Verra's Soil Enrichment Protocol, to the extent that soil sampling captures the effects of biochar priming, soil carbon projects employing other eligible soil health practices may benefit from the soil organic carbon gains associated with biochar. The impact and uncertainty surrounding these priming dynamics are described in more detail in section 4.3.

Enhanced weathering is another promising carbon removal technology that is expected to generate interest within carbon markets. While there is not an established methodology for enhanced weathering, Microsoft, one of the more influential buyers of carbon credits, indicated in its carbon procurement plan that it would be interested in purchasing credits produced from enhanced weathering approaches. Puro.Earth also has a pilot project in Surinam listed, though there is no corresponding methodology that has been produced to establish project development standards. The project, started by the Carbon Neutral Initiative, is part of Puro.Earth's "pre-CORC" (CORC is Puro'Earth's terminology for a carbon credit) program that allows for early-stage projects from "high-quality" carbon removal technologies to track credits and secure offtake agreements without a formal methodology. Should waste heat from biochar enhance the rate of carbon removal in enhanced weathering (as suggested in section 2.6.3), the synergy between these projects could enhance value capture. As a long duration carbon removal technology, enhanced weathering represents another high-priced carbon crediting opportunity. There are still technical gaps in the monitoring or environmental gains from enhanced weathering (Amann and Hartmann, 2022), and while there may be "pre-market" opportunities to sell credits ahead of adoption of a methodology, it represents a riskier project type than biochar at this stage.

4.5. Potential Revenue Streams

The economic conditions surrounding carbon markets are another critical dimension that impacts the viability of offset development. Voluntary carbon markets have experienced significant economic growth, quadrupling in size between 2020 and 2022 to more than $2 billion (Ecosystem Marketplace 2022). The market now represents over $1 billion globally. By 2050, the market is expected to grow to $200 (Watson 2020)-$550 (Henze 2022) billion.

This increasing demand has not necessarily translated to predictable offset pricing. Because of the prevalence of private, "over-the-counter" carbon sales, there is limited price transparency in carbon markets. The largest public survey of offset transactions run by the Forest Trends Initiative (FTI), estimates an average voluntary offset price of $3 per ton in 2021, but that number is heavily influenced by large international forestry projects, older credit vintages, as well as energy efficiency and renewable energy projects that are atypical in the United States market. Several public carbon procurement and sales reports have increased pricing expectations. Microsoft disclosed an average carbon price of $19.40/ton for the 1.5 million tons of offsets it procured in 2022. Stripe's carbon removal procurement averaged "a couple hundred dollars per ton," with prices ranging from $75 to $2052 per ton (Meyer 2022).

The range in offset prices reveals changing buyer preferences surrounding carbon quality and project attributes. Many firms are placing higher premiums on carbon removal, rather than merely avoiding emissions. Projects whose emissions have a low risk of "reversal" - i.e. they can demonstrate durable carbon removal for hundreds or even thousands of years - facilitate premium pricing. It is unclear to the extent that the norms established by pioneer buyers like Microsoft and Stripe, will be replicated at scale by other voluntary carbon buyers or compliance programs that often minimize the differences between projects and treat carbon credits from different sectors as equivalent commodities. Bloomberg NEF has modeled various scenarios for carbon markets, including a scenario at an average of $11 per ton by 2030, should credits from avoided emissions projects (perceived as more prevalent and lower quality) help meet a modest level of voluntary corporate emissions goals (Fig. 11) (Henze 2022). An alternative scenario that prioritizes carbon removal technologies, and sees more aggressive corporate greenhouse gas commitments, puts carbon pricing at $224 per ton by 2029 before stabilizing at $120 per ton in 2050. This range of uncertainty makes modeling long term project economics at scale a challenge.

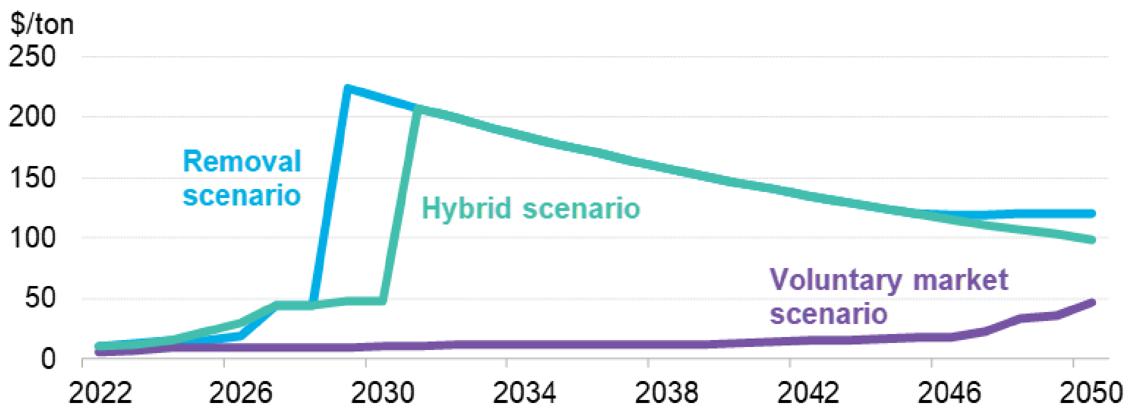


Figure 11. Price forecasts for carbon offsets following three scenarios (Henze, 2022).

Carbon projects also carry costs for the ongoing monitoring, reporting, and verification of credits, in addition to registration and marketing of credits. Projects at a minimum will have annual site visits with verifiers to review project documentation and ensure facility compliance. The annual verification process for facility-based projects like biochar production cost $10,000-$20,000 depending on the complexity of the methodology, computational complexity in modeling credits, the extent to which a verifier must review new scientific literature, the degree to which facilities are exposed to additional regulatory complexity (such as air permits or wastewater concerns), the volume of paperwork required to review, and the number of in-person site visits required.

The marketing of credits will vary depending on whether a project works with an independent carbon project developer, who may bring relationships to carbon buyers and help de-risk challenges in verification and project monitoring but will likely take an equity interest in the project. Carbon brokers may also be utilized to market credits and leverage market intelligence to influence long term pricing strategies. For higher volume projects those brokers may take a 3-5% fee on the gross carbon revenue - though for smaller, more bespoke projects, a higher fee may apply.

Registries also charge fees to registered projects. Figure 12 below represents Verra's fee schedule, which includes fees for registering a project, issuing credits, and utilizing a Verra methodology. Verra's schedule sees fees increase once projects hit 10,000 tons of credits, and projects steadily receive some economies of scale at higher volumes of credits. The economic model we present in Section 5 includes an estimated fee of 20 cents per ton of credits generated.

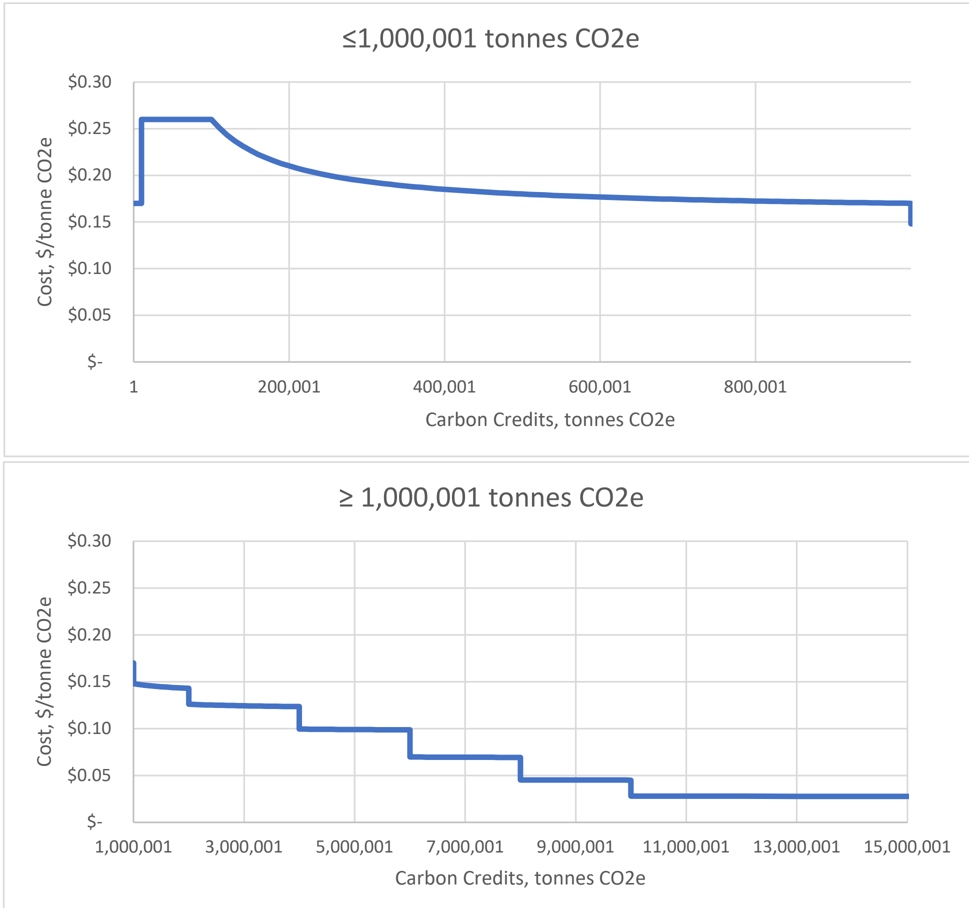


Figure 12. Verra fee schedule per carbon credit (tonne of CO2e) produced in a registered project. These fees exclude a one time, $500 fee to open an account with Verra. Fees for projects under 10,001 credits are $0.17 per credit.

5. Assessment of Opportunities

5.1. Approach to incorporating climate, economic, agronomic, and geographic factors

Our approach involved several steps. First, we assessed the amount and geographical location of the crop residues considered to be sustainably available using county-level data from the interactive version of the US Department of Energy's Billion Ton Report (USDOE 2016). These data identified the major cropping systems that provide biomass feedstock potentially available for biochar production. The results show that cereal straws (primarily wheat straw) and woody waste biomass recovered from orchard and vineyard trimming operations are the two major types of residual biomass available from cropping systems in the three-state Pacific Northwest region. Next, we used the CroplandCROS online application with the 2021 Cropland Data Layer (USDA-NASS 2022) to map the locations of farms in the Pacific Northwest that grow the crops providing these biomass feedstocks (Figs. 13 and 14).

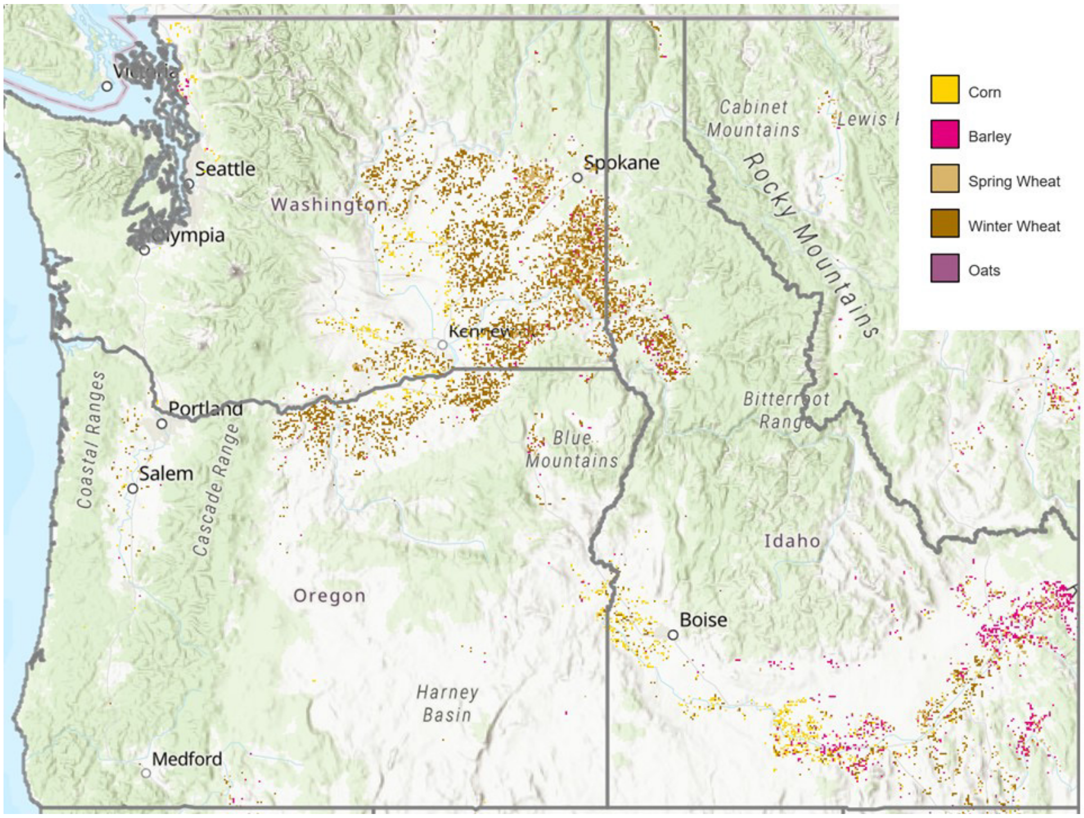


Figure 13. Location of agricultural biomass from cropping residues (cereal straw) in the Pacific Northwest (WA, OR, ID) (USDA-NASS 2022).

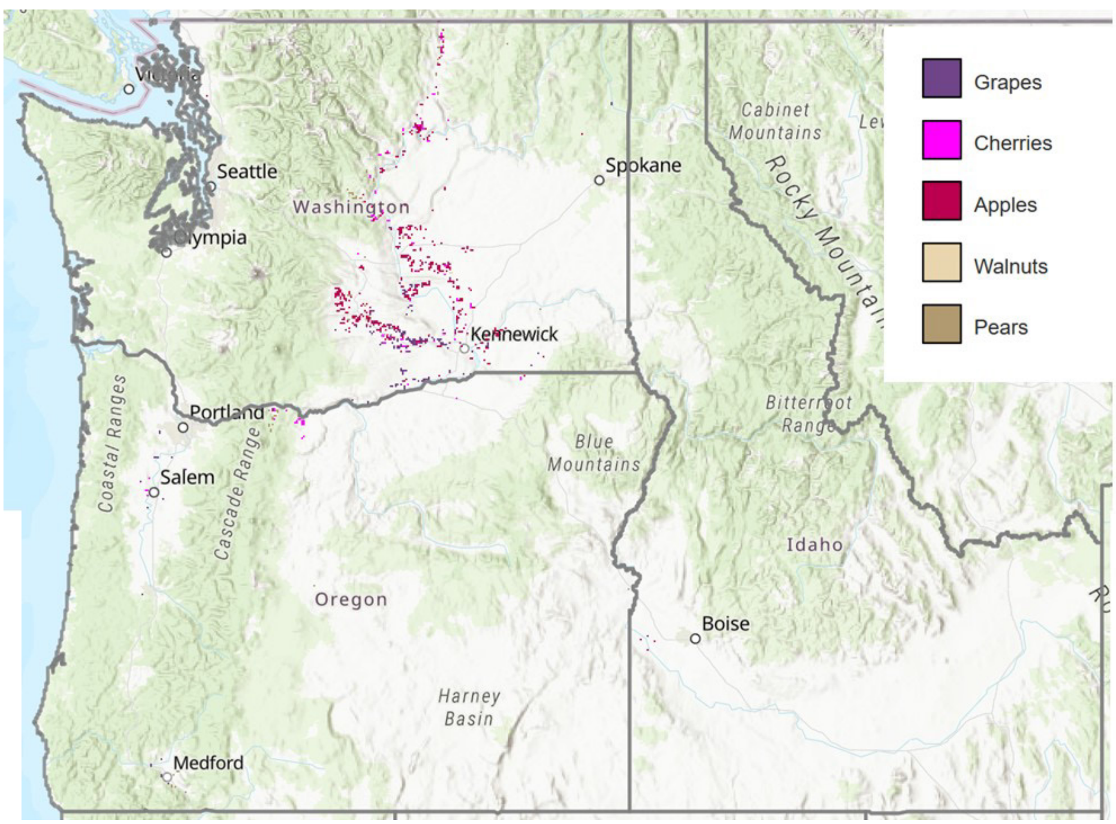


Figure 14. Location of woody waste biomass (trimmings from orchard and vineyard operations) in the Pacific Northwest (WA, OR, ID) (USDA-NASS 2022)

As can be seen, the highest density of biomass production is in the Columbia Basin and mid-Columbia Valley of Washington and Oregon, with additional production in the Snake River Plane of Idaho and the Willamette Valley of Oregon.

We used this geographic information, coupled with USDA-NASS county-level statistics about farm size, to select the Willamette Valley region, which has a high proportion of small farms and a relatively low density of biomass production, for further analysis of biochar economic viability. The location of crop production in this 9-county region of northwestern Oregon is shown in Fig. 15, together with a circle representing a 5-mile radius typical of that required to support a small- to mid-scale biochar production facility. Crop production statistics for the nine counties included in the Willamette Valley are given in Table 6. The available biomass can support about 50-200 biomass conversion facilities of the size considered in this report, suggesting there is plenty of opportunity to develop a mature biochar industry in this region.

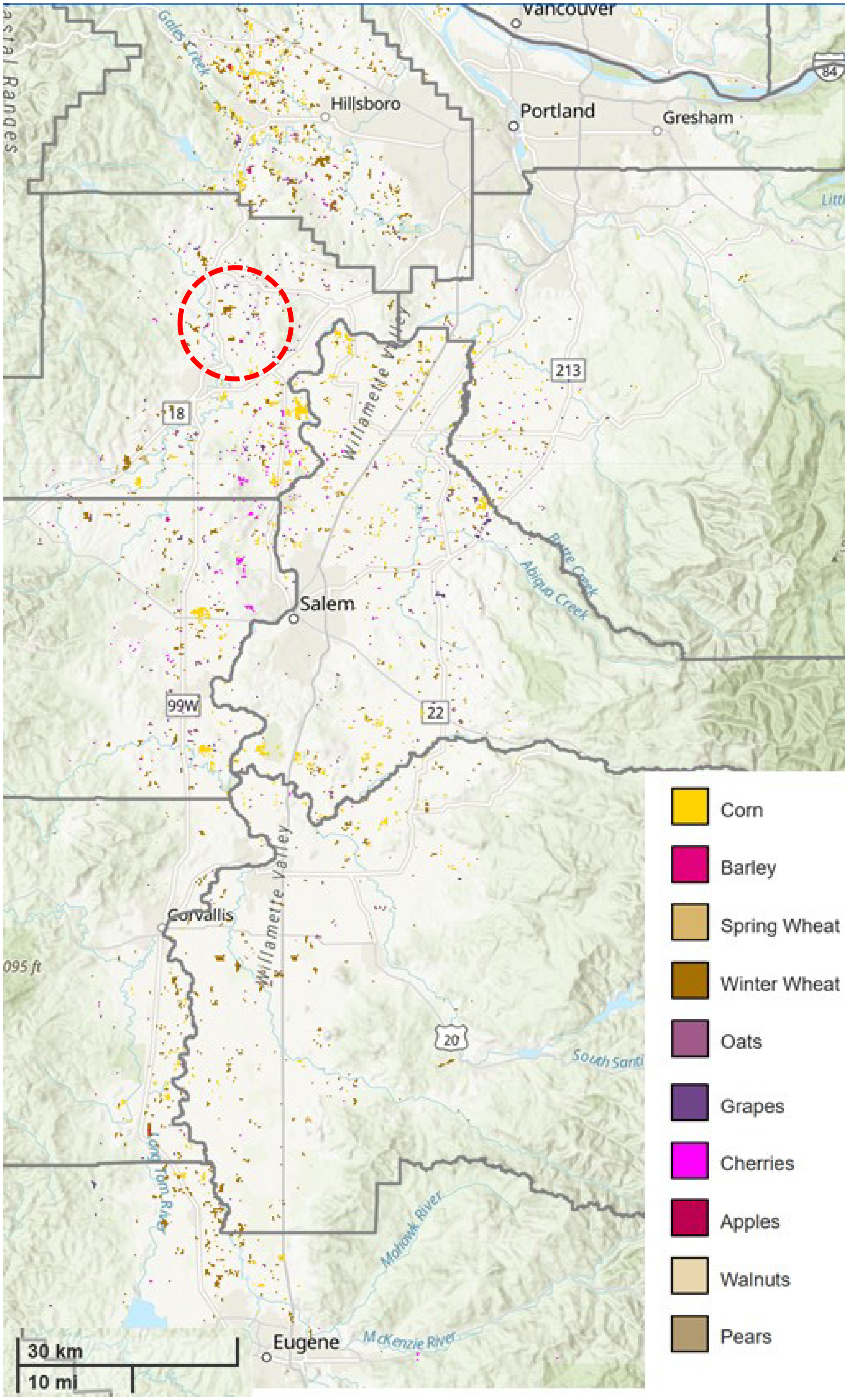


Figure 15. Test Region—Willamette Valley (Oregon)—circle shows 5-mile radius (~ 80 square miles) for a biomass conversion facility located in a small-farming region. (USDA-NASS 2022)

Table 6. Estimates of available agricultural and waste biomass in the Willamette Valley in 2022 (USDOE 2016, USDA-NASS 2017). Mean data are highlighted in grey.

Biomass Resource	County	Harvested Acres	Fraction of County Cropland	Production per acre, dry tons	Total Production, dry tons	Percent of County Biomass
Wheat straw	Benton	0	0.0%	--	0	0.0%
Wheat straw	Clackamas	1256	1.5%	0.50	628	51.0%
Wheat straw	Lane	5599	5.7%	1.93	10808	83.2%
Wheat straw	Linn	2241	0.9%	2.41	5402	93.5%
Wheat straw	Marion	13161	5.6%	1.85	24317	85.8%
Wheat straw	Multnomah	885	5.7%	1.94	1712	91.5%
Wheat straw	Polk	11679	10.9%	1.25	14604	74.1%
Wheat straw	Washington	11865	15.7%	1.40	16560	85.5%
Wheat straw	Yamhill	11791	10.4%	1.12	13184	62.2%
Subtotals or Means:		**58477**	**5.6%**	**1.49**	**87215**	**78.4%**
Orchard and Vineyard Trimmings*	Benton	4768	6.9%	0.15	692	100.0%
Orchard and Vineyard Trimmings	Clackamas	7362	8.8%	0.08	604	49.0%
Orchard and Vineyard Trimmings	Lane	6707	6.9%	0.32	2177	16.8%
Orchard and Vineyard Trimmings	Linn	8689	3.6%	0.04	377	6.5%
Orchard and Vineyard Trimmings	Marion	22930	9.7%	0.18	4040	14.2%
Orchard and Vineyard Trimmings	Multnomah	265	1.7%	0.60	160	8.5%
Orchard and Vineyard Trimmings	Polk	18518	17.3%	0.28	5101	25.9%
Orchard and Vineyard Trimmings	Washington	10493	13.9%	0.27	2808	14.5%
Orchard and Vineyard Trimmings	Yamhill	28197	24.8%	0.28	8003	37.8%
Subtotals or Means:		**107929**	**10.4%**	**0.22**	**23962**	**21.6%**
TOTALS or MEANS:		**166406**	**16.0%**	**0.67**	**111177**	

*Acreages are for *bearing and non-bearing* orchards and vineyards in 2017 (USDA-NASS); production of trimmings per acre in each county is estimated from total production for 2022 (BTR, 2016) divided by the 2017 acreage.

To assess climate impacts and economic viability, we identified four commercially available biochar production technologies [based on prior experience and contacts in the biochar industry (e.g., Amonette et al. 2021) and the availability of climate-relevant and production-cost data], that offer maximum climate benefits at the relatively small operational scale associated with the farming systems of interest in this project. These technologies are similar to those discussed in Section 2.2 and include

- a manual-feed flame cap kiln (e.g., Ring-of-Fire kiln, Wilson Biochar Associates, https://wilsonbiochar.com/),
- a containerized automated pneumatic-feed gasifier system (Qualterra, https://qualterraag.com , formerly a division of NuPhY, which acquired Ag Energy Systems),
- a containerized automated auger-driven pyrolytic gasifier system *without* an optional afterburner for emissions control (Advanced Renewable Technology, International, ARTi, https://www.arti.com/), and
- a batch, computer-controlled high-temperature slow-pyrolysis kiln system with a propane afterburner for emissions control (Biochar Now, https://biocharnow.com/).

Nominal specifications for these technologies are summarized in Table 7.

Table 7. Overview of technical parameters for the four biochar production technologies selected for detailed climate impact and economic analysis.

Biochar Technology	Feedstock Processing Capacity (for Single Unit)			Biochar Carbon Efficiency	Number of Units in Array		Annual Biochar Production Capacity, odt[1]			
							Typical Array		Maximum Efficiency	
	odt/day	days/year	odt/year	%	Typical	Maximum Efficiency	Wheat Straw	Woody Trimmings	Wheat Straw	Woody Trimmings
Manual-Feed Flame Cap Kiln	0.73	180	131	35, 40[2]	8	8	239	253	239	253
Automated Gasifier	1.31	310	405	35, 43[2]	3	5	279	344	466	574
Automated Pyrolytic Gasifier w/o Afterburner	7.26	310	2250	40, 45[2]	1	5	578	620	2890	3101
Batch High-Temperature Slow-Pyrolysis Kiln	0.86	310	265	40, 45[2]	12	(30), 60[3]	823	831	4115	4155

[1] oven dry tonnes per day
[2] first value for wheat straw, second value for woody trimmings
[3] maximum efficiency is reached with 30 kilns; 60 kiln array (two 30-kiln arrays) is shown for comparison with automated pyrolytic gasifier w/o afterburner

The climate benefits were modeled for two major feedstock types using a simple time-sensitive LCA approach that considered C content of the biomass and biochar, carbon efficiency of production, emissions of CO_2, CH_4, N_2O and black-carbon particulates (soot aerosols), and stability of the biochar after incorporation into soil. In most instances, we used existing (published and proprietary) data to follow carbon through the production system and to model emissions. A mean annual soil temperature of 12.75°C was used for the region of interest (Bates, 1975), in conjunction with the approach outlined by Woolf et al. (2021), to model the biochar stability in soil. No attempt was made to model soil organic matter priming (as done in Amonette, 2021), however, as that effort required resources beyond the scope of this phase of the project. For two technologies, we also considered the impacts of bioenergy production and improved levels of particulate removal on overall climate benefits. Model parameters for the biochar technologies are provided in Table 8.

Table 8. Model parameters for biochar conversion technology scenarios used in life cycle assessment. Shading indicates range of variability/degree of confidence in data (green = low variability/high confidence, white = moderate variability/confidence, red = high variability/low confidence).

Model Parameter	Units	Biomass Conversion Technology							
		Flame-Cap Kiln	Gasifier	Gasifier w/Energy	Pyrolytic Gasifier	Pyrolytic Gasifier w/Energy	Pyrolytic Gasifier w/Low Soot	Pyrolytic Gasifier w/Energy + Low Soot	Slow Pyrolysis Kiln
		Wheat Straw Feedstock							
C content of biomass	kg C / kg dry biomass	0.4352	0.4352	0.4352	0.4352	0.4352	0.4352	0.4352	0.4352
Biochar C efficiency	kg biochar C / kg biomass C	0.352	0.354	0.354	0.396	0.396	0.396	0.396	0.398
C content of biochar	kg biochar C / kg biochar	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Biochar decay rate	half-life, yr	505	505	505	505	505	505	505	505
CH_4 emission factor	g CH_4 / kg dry biomass	4.107	0.043	0.043	0.073	0.073	0.073	0.073	0.010
N_2O emission factor	g N_2O / kg dry biomass	0.009	0.102	0.102	0.185	0.185	0.185	0.185	0.046
Soot emission factor	g soot / kg dry biomass	0.264	0.002	0.002	0.125	0.125	0.002	0.002	0.002
Fossil fuel offset factor	g CO_2eq / g dry biomass	-0.007	-0.015	0.257	-0.001	0.256	-0.048	0.209	-0.097
		Woody Trimmings Feedstock							
C content of biomass	kg C / kg dry biomass	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Biochar C efficiency	kg biochar C / kg biomass C	0.4	0.434	0.434	0.45	0.45	0.45	0.45	0.453
C content of biochar	kg biochar C / kg biochar	0.81	0.75	0.75	0.80	0.80	0.80	0.80	0.85
Biochar decay rate	half-life, yr	505	505	505	505	505	505	505	505
CH_4 emission factor	g CH_4 / kg dry biomass	4.107	0.043	0.043	0.073	0.073	0.073	0.073	0.010
N_2O emission factor	g N_2O / kg dry biomass	0.009	0.102	0.102	0.185	0.185	0.185	0.185	0.046
Soot emission factor	g soot / kg dry biomass	0.264	0.002	0.002	0.125	0.125	0.050	0.050	0.002
Fossil fuel offset factor	g CO_2eq / g dry biomass	-0.007	-0.015	0.202	-0.001	0.222	-0.048	0.175	-0.097

We selected two alternative biomass scenarios for each feedstock type (Table 9) to complete the LCA, which involved a comparison of total emissions from an alternative scenario and a biochar production technology scenario modeled on an annual basis out to 200 years. As discussed in Sections 3.4 and 3.5, for each scenario pair, the total emissions for the alternative biomass scenario were subtracted from those for the biochar production technology at each time step in the analysis. Results less than zero show a net climate benefit (i.e., the biochar technology is carbon-negative relative to the alternative biomass scenario). Two emission regimes were modeled, a single annual emission pulse (used in current carbon-credit methodologies discussed in Section 4) and repeated annual emission pulses as used by Woolf et al. (2010) and Amonette (2021). By summing the single annual-emission pulses, the repeated annual-emission pulse regime provides a more realistic assessment of climate benefits for long-term mitigation strategies involving several individual projects. The single-pulse approach, however, offers the benefit of simplicity and is appropriate for individual projects.

Table 9. Model parameters for alternative biomass scenarios used in life cycle assessment.

Model Parameter	Units	Biomass Feedstock			
		Wheat Straw		Woody Trimmings	
		ALT_1: Natural Biomass Decay	ALT_2: Compost then Soil Decay	ALT_3: Slash Pile Burn	ALT_4: Chip and Spread
C content of biomass	kg C / kg dry biomass	0.4352	0.4352	0.49	0.49
Biomass decay rate	half-life, yr	0.69	0.44	--	5
Biochar C efficiency	kg biochar C / kg biomass C	--	--	0.02	--
C content of biochar	kg biochar C / kg biochar	--	--	0.80	--
Biochar decay rate	half-life, yr	--	--	505	--
CH_4 emission factor	g CH_4 / kg dry biomass	0	2.86	5.72	0
N_2O emission factor	g N_2O / kg dry biomass	0	0.27	0.22	0
Soot emission factor	g soot / kg dry biomass	0	0	0.222	0
Fossil fuel offset factor	g CO_2eq / g dry biomass	0	0	0	-0.0048

Because biochar technology releases a large fraction of the biomass carbon during the production stage, a carbon debt is created in some instances that delays the time before a net climate benefit is obtained. The period required to retire the carbon debt (i.e., the period when the LCA shows higher emissions by biochar technology than the alternative scenario) is termed the carbon-payback period. We used the annualized time-sensitive LCA approach to determine the carbon-payback period for those instances in which it applies as one useful parameter with which to compare the climate impacts of biochar production technologies. As discussed by DeHue and co-workers (2007, 2013), technologies yielding carbon-payback periods of ten years or less are considered fully sustainable, whereas carbon-payback periods on the order of a century or longer are clearly unsustainable.

Our assessment of the potential economic viability of biochar considers the same biochar production systems and feedstocks as the climate impact analysis, but only one alternative biomass pathway for each feedstock is considered ("natural biomass decay" for wheat straw and "chip and spread" for woody trimmings), in conformance with the default biomass-decay options of the carbon credit mechanisms. We developed a spreadsheet model that incorporates broader financial information (such as the prime lending rate, depreciation rate, mortgage term, and marginal corporate income tax) as well as market rates for electricity, industrial land and biomass, and assumptions about transportation distances, to complement the basic compositional data for biomass and biochar used in the climate impact model. The broader financial information was used to calculate the fixed charge rate, which annualizes capital costs for easy comparison with other annualized parameters such as biochar production rate. We calculated the cost of production and the number of carbon credits (tonnes CO2e at 100 years) produced per unit of biochar using information obtained from the manufacturers. Carbon credits were calculated as the difference between the baseline emissions of the biomass ["natural biomass decay" (Alt_1) for wheat straw and "chip and spread" (Alt_4) for woody trimmings] and the sum of the emissions during biochar production and from biochar decay in soil over 100 years (Fig. 16).

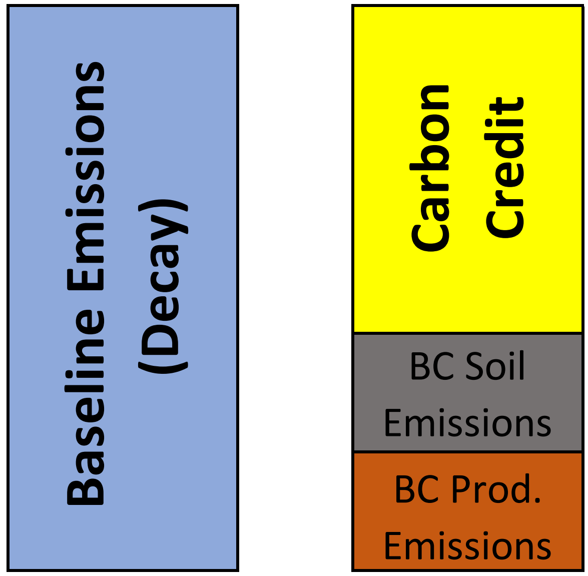


Figure 16. Schematic of carbon credit calculations showing baseline emissions on left and biochar production/soil decay emissions on right. Subtraction of biochar emissions from baseline emissions yields the carbon credit in tonnes of CO2e.

The variable and fixed input parameters used in our economic model are shown in Table 10. We assumed the current market price for biomass ($40/dry tonne) although whether this is incurred will depend on the business model adopted. We did not estimate potential income from generation of electricity or use of waste heat, as capital and operational information was not readily available from the manufacturers and our analysis of the climate benefits (Section 5.2.1) suggested that energy capture had marginal value. Also, we did not consider potential income streams from integration with composting operations. The bottom line in our economic analysis is the breakeven cost for a carbon credit (i.e., $/tonne CO2e) which is the total annual cost of production divided by the number of carbon credits generated annually.

Table 10. Variable input parameters, constants, and calculated factors used in the production economics modeling.

Variable Inputs		
Prime Lending Rate:	5.50%	
Years to Retire Debt:	10	
Years to Depreciate:	10	
Marginal Corporate Income Tax:	21.0%	
Diesel Fuel:	$5.50	$/gall
Propane Fuel:	$1.63	$/gall
Carbon Storage Credits:	$100.00	$/tonne CO2
Electricity (industrial):	$60.80	$/MWh
Electricity (residential):	$104.00	$/MWh
Electricity Emission Factor:	147	kg CO2/MWh
Biomass Cost at Farm Gate (Wheat Straw)	$40.00	$/tonne
Biomass Carbon Content (Wheat Straw):	43.52%	g C/g BM
Biomass Cost at Farm Gate (Woody Trimmings):	$40.00	$/tonne
Biomass Carbon Content (Woody Trimmings):	49.00%	g C/g BM
Biomass Transport Distance:	10	miles
Biochar Transport Distance:	10	miles
Biochar Soil Permanence Factor:	87.2%	biochar C remaining at 100 years
Carbon Registry Administrative Fee:	0.20	$/tonne CO2e
Annual Carbon Credit Verification Costs:	$15,000	$
Industrial Site Cost:	$25,000	$/acre
Transport Energy (diesel trucks):	2.426	MJ/tonne-km
Transport Energy (hybrid diesel rail):	0.209	MJ/tonne-km

Constants and Calculated Factors		
Annual Depreciation Factor:	1.0210	
Annual Mortgage Factor:	0.1327	
Fixed-Charge Rate:	13.55%	
Miles to Kilometers:	1.609	km/mile
Carbon to CO_2:	3.664	g CO2/g C
Tons to tonnes:	0.907	tonnes/Ton
CH4 100-year Global Warming Potential:	30.4	g CO2e/g CH4
N2O 100-year Global Warming Potential:	284	g CO2e/g N2O
Soot 100-year Global Warming Potential:	940	g CO2e/g soot
Propane Emission Factor:	5.750	kg CO2/gall
Diesel Energy Content:	144.945	MJ/gall
Diesel Emission Factor:	163.450	lbs CO2/MBTU
Diesel Emission Factor:	10.190	kg CO2/gall
Diesel Emission Factor:	70.302	g CO2/MJ

5.2. Results: Identification of optimal combinations

5.2.1. Climate impacts

Our initial assessment of climate impacts involves calculations of net emission curves as a function of time that represent the LCA results for each production-technology/biomass-alternative combination. This type of analysis (Fig. 17) allows immediate visualization of the carbon payback period for each combination as the point at which the net emission curve crosses from positive net emissions (pink shaded zone) to negative net emissions (green or white zones). For the wheat-straw/natural biomass decay scenario shown, the gasifier and the high-temperature slow-pyrolysis kiln technologies are immediately carbon-negative and thus have no carbon payback periods. The other two technologies have carbon payback periods of 5 years (pyrolytic gasifier) and 21 years (flame cap kiln). Thus, in this scenario, three of the biochar production technologies are considered fully sustainable whereas the flame cap kiln is not.

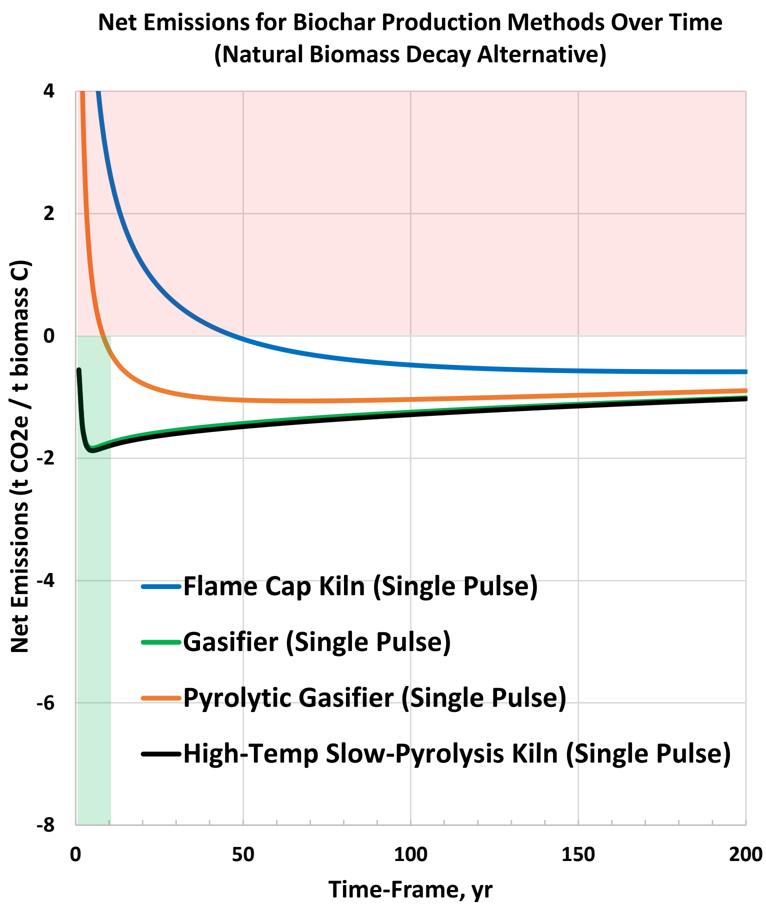


Figure 17. Net emission curves for single biochar production pulses from wheat straw feedstock assuming natural biomass decay as the alternative biomass Path.

The results in Fig. 17 show the changes in net emissions over two centuries expected for a one-time (i.e., single-year) production of biochar at the start of Year 1. This is the approach commonly taken to evaluate individual projects in the voluntary credit market because it allows flexibility from year to year to account for changes in production methods, feedstocks, and even alternative biomass pathways, as needed. Because the decadal timeframe for removal of long-lived greenhouse gases from the atmosphere results in "carryover" emissions from one production year to the next, however, the single-pulse approach does not give an accurate portrayal of the cumulative climate impacts of a biochar industry that operates continuously over many years. These impacts can be estimated by a "repeated annual pulse" curve generated by averaging the single-pulse curves contributing to each year of production. For example, with the repeated annual pulse approach, the net emissions for Year 5 of a continuously operating project would be the average of five identical single-pulse curves offset from the origin by 0, 1, 2, 3, and 4 years.

An idea of how the single- and repeated annual pulse approaches differ is given in Fig. 18 for the same wheat-straw/natural biomass decay scenario shown in Fig. 17. For the pyrolytic gasifier and flame cap kiln, the net emissions are significantly higher for the repeated annual pulse approach (dotted lines) than for the single-pulse (solid lines) approach. Further, the carbon payback period for the pyrolytic gasifier increases from 8 to 53 years and that for the flame cap kiln from 47 to more than 200 years. For the other two biochar production methods, small increases in net emissions are predicted with the repeated annual pulse approach. These differences are driven by the relative emissions of soot (black carbon aerosols) and methane, which are higher for the pyrolytic gasifier and flame cap kiln than for the gasifier and slow pyrolysis kiln production methods (Table 8).

Although the repeated annual pulse approach provides a more accurate portrayal of the cumulative climate impacts of a biochar industry, the focus in this report on carbon credits leads us to present single-pulse data for the remainder of this section. Repeated annual pulse data for each scenario discussed in this section are given in Appendix A.

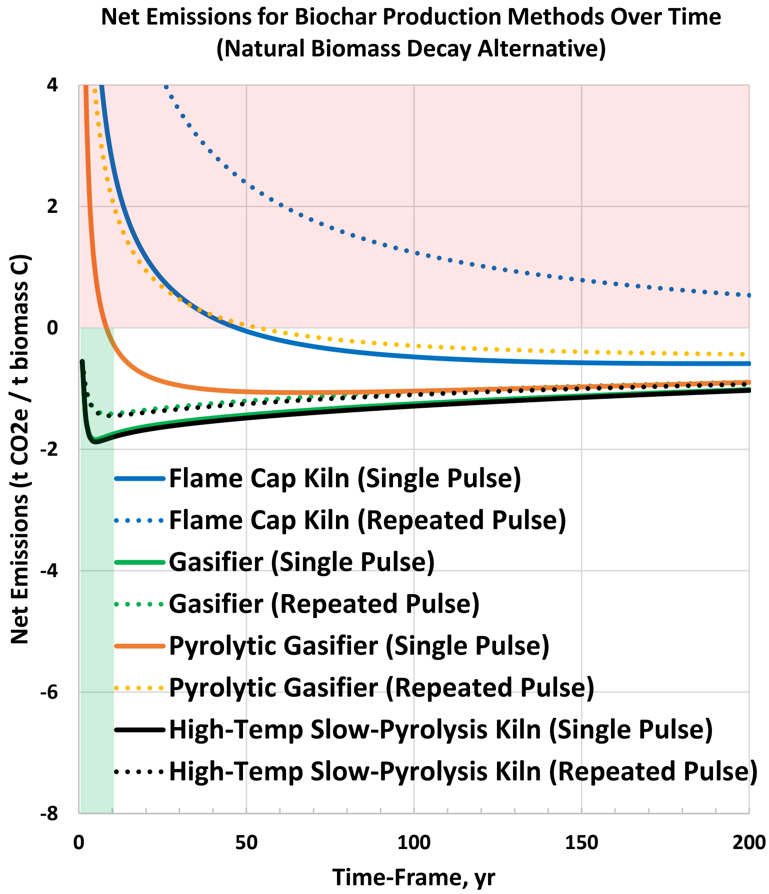


Figure 18. Net emission curves for single and repeated annual biochar production pulses from wheat straw feedstock assuming natural biomass decay as the alternative biomass path.

An overview of the relative effects of different alternative biomass pathways and of energy capture by the two gasifier technologies on net emission curves (Fig. 19) shows the dominant impact of alternative biomass pathways. When woody trimmings would be disposed by slash pile burns (Fig. 19 lower left panel), all four biochar production technologies provide sustainable carbon payback periods. The large soot and methane emissions from the slash piles dwarf those of the biochar production technologies. Consequently, when the difference of the two biomass pathways (i.e., slash pile burning vs. biochar production) is calculated, the biochar production technologies have a huge advantage in net emissions during the first decade or two. However, soot and methane have relatively short lifetimes in the atmosphere and the difference between the two biomass pathways narrows at longer time periods leading to a “rebound” in the net emissions associated with biochar production.

Biochar technology is not as dominant when the same woody trimmings would have been disposed by chipping them and spreading them as surface mulch (Fig. 19, lower right). In this instance, only the three modern biochar production technologies are fully sustainable. Addition of an energy-capture capability to the two gasifier units decreases the net emissions by only 0.2-0.3 tonnes CO2e/tonne biomass C after 100 years (Fig. 19, all panels). This result is largely due to the low carbon intensity of the primary energy supply in the Pacific Northwest.

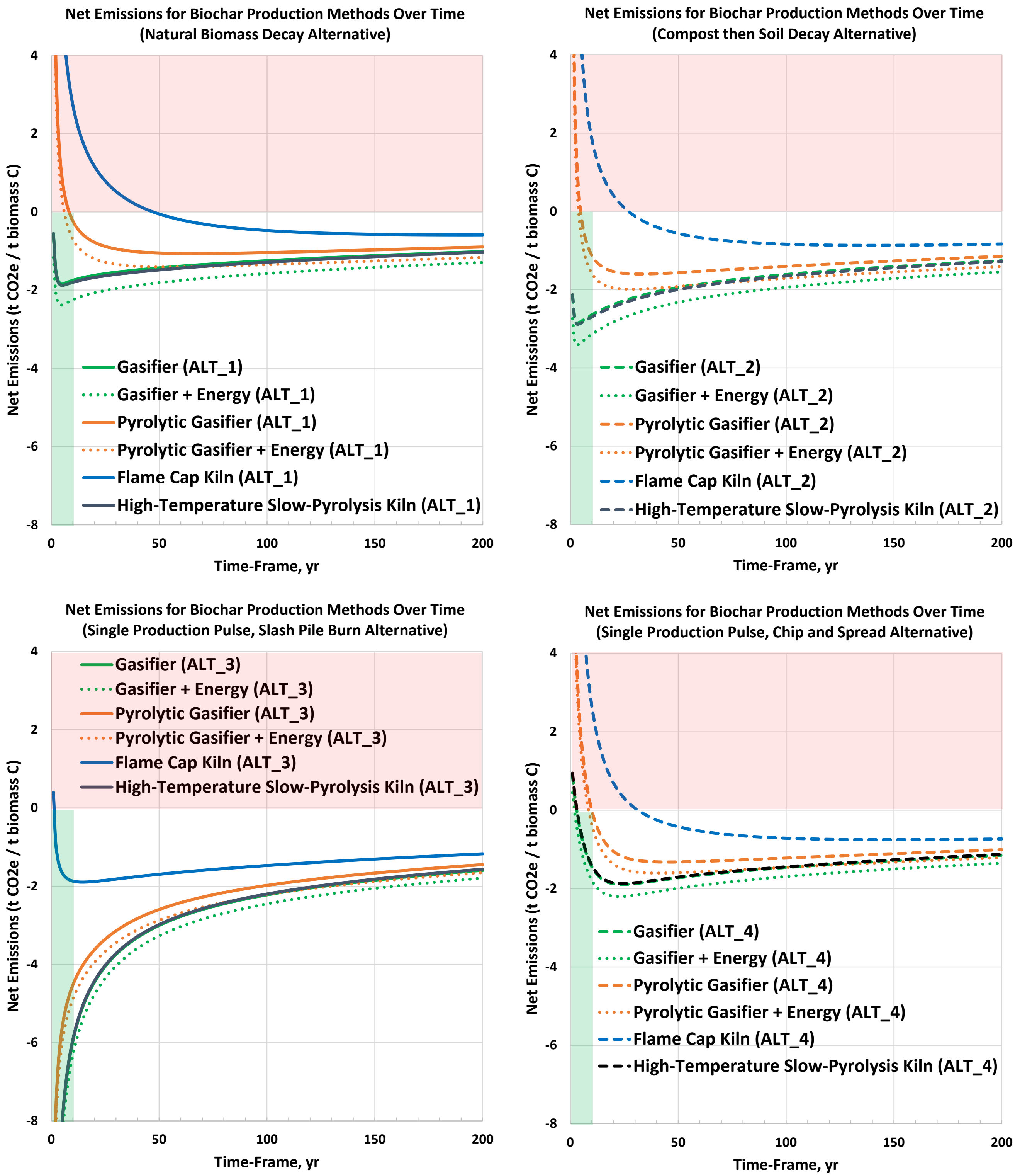


Figure 19. Net emission curves for one-time, single-year biochar production pulses for wheat straw (top panels) and woody trimmings (bottom panels) for each of the four alternative biomass pathways. Curves for the addition of energy capture capabilities by the two gasifiers are also shown.

In contrast to the low impact of energy capture/use capabilities, addition of particulate matter pollution control equipment yielding low soot aerosol levels (emission factors of 0.002 g soot/kg biomass) for the pyrolytic gasifier significantly shortens its carbon payback periods (Fig. 20, all panels). The low soot aerosol

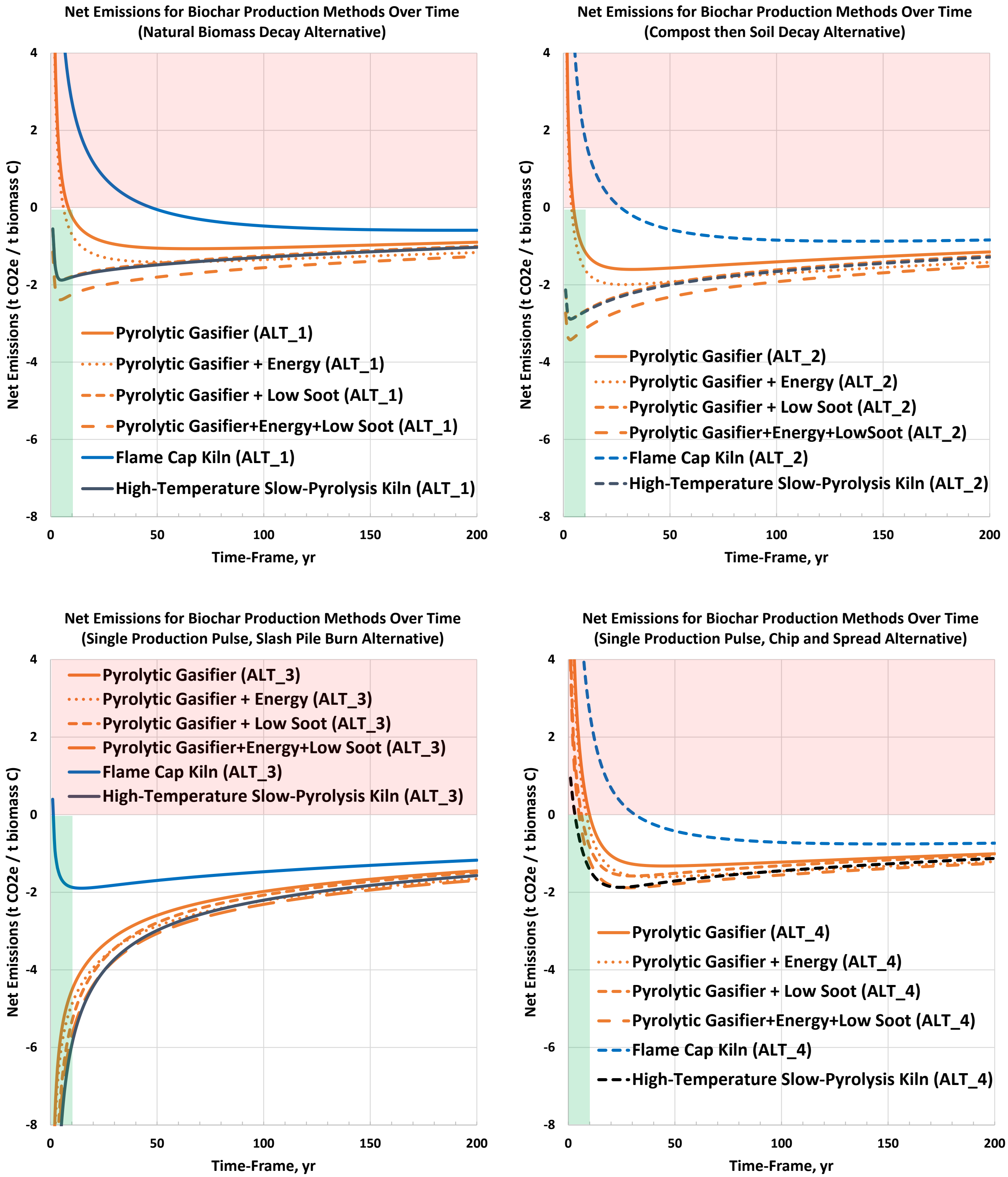


Figure 20. Net emission curves for single-year biochar production pulses for wheat straw (top panels) and woody trimmings (bottom panels) for each of the four alternative biomass pathways and three of the four biochar production technologies. For the pyrolytic gasifier, curves for the addition of energy capture, soot removal, and both capabilities are also shown.

levels for the gasifier system likely stem from the higher temperatures employed (ca. 700-800°C) relative to those for the pyrolytic gasifier system (ca. 500-600°C). Efficient soot-removal technology is already employed by the high-temperature slow-pyrolysis kiln system and cannot be added to the flame cap kiln system. Clearly, for most biochar production technologies, investment in soot-removal technology is critical to maximizing overall climate performance.

A summary of the climate impacts of the different combinations of biomass conversion technology, feedstock, and alternative biomass path is provided in Table 11. In addition to carbon payback periods, the net emissions after 100 years are provided in terms of tonnes of CO2e avoided per tonne of biomass C, biomass, or biochar produced. The data cells in the table are color coded to indicate their level of sustainability, with green being fully sustainable, and red unsustainable. Intermediate colors are used for carbon payback periods of 11-20 years (beige) and 21-50 years (light orange). Also shown are the biomass C contents and, for each biochar technology, the biochar C efficiencies and C contents that are used to calculate the CO2e-per-unit-biochar dataset. A similar summary table using the repeated annual production approach is provided in Appendix A.

The main results of the climate impacts analysis (Table 11) show that the high-temperature slow-pyrolysis kiln, gasifier, and pyrolytic-gasifier systems provide fully sustainable climate outcomes for all scenarios considered. For the flame-cap kiln system, C-negative net emissions are obtained after 100 years in all scenarios but high soot and CH_4 emissions prevent it from having sustainable C-payback periods for three out of four alternative biomass scenarios; The flame cap kiln system performs well, however, with woody biomass feedstocks when slash pile burning is the alternative biomass scenario. Energy capture, while adding to the C-negative results of the two gasifier systems, is of secondary importance in the Pacific Northwest due to the already low C intensity of the energy supply.

The alternative biomass scenario and choice of feedstock strongly affect the predicted climate impacts. The largest net-negative emissions are obtained from biochar production when slash-pile burning of woody trimmings is the alternative. Conversely, the smallest net-negative emissions are obtained when natural biomass decay of wheat straw is the alternative, averaging 42-49% less than those seen for the slash-pile burning scenarios. Composting followed by soil decay of wheat straw and chipping and spreading of woody trimmings yield comparable average net-negative emissions that are 25-36% less than those for slash-pile burning of woody trimmings. The higher C and lignin contents of woody trimmings relative to wheat straw lead to more efficient biochar production per unit of biomass and thus contribute to these net-negative emission trends.

Table 11. Carbon payback periods (time needed to attain carbon negativity) and net emissions after 100 years for different combinations of biomass conversion technology, feedstock, and alternative biomass path assuming a single-year production pulse.

		Single Pulse							
Biomass Conversion Technology		Flame-Cap Kiln	Gasifier	Gasifier w/Energy	Pyrolytic Gasifier	Pyrolytic Gasifier w/Energy	Pyrolytic Gasifier w/Low Soot	Pyrolytic Gasifier w/Energy w/Low Soot	Slow Pyrolysis Kiln
Feedstock	**Alternative Biomass Path**	Carbon Payback Period, years							
Wheat Straw	ALT_1 Natural Biomass Decay	47	0	0	8	5	0	0	0
	ALT_2 Compost then Soil Decay	26	0	0	4	3	0	0	0
Orchard and Vineyard Trimming	ALT_3 Slash Pile Burn	1	0	0	0	0	0	0	0
	ALT_4 Chip and Spread	31	2	1	9	8	6	5	3
		Net emissions after 100 years, t CO2e / t Biomass C							
Wheat Straw	ALT_1 Natural Biomass Decay	-0.48	-1.25	-1.58	-1.04	-1.35	-1.25	-1.56	-1.29
	ALT_2 Compost then Soil Decay	-0.84	-1.61	-1.94	-1.40	-1.71	-1.61	-1.92	-1.65
Orchard and Vineyard Trimming	ALT_3 Slash Pile Burn	-1.47	-2.22	-2.45	-1.98	-2.22	-2.07	-2.31	-2.20
	ALT_4 Chip and Spread	-0.71	-1.46	-1.69	-1.22	-1.46	-1.31	-1.55	-1.44
		Net emissions after 100 years, t CO2e / t Biomass							
Wheat Straw	ALT_1 Natural Biomass Decay	-0.21	-0.54	-0.69	-0.45	-0.59	-0.54	-0.68	-0.56
	ALT_2 Compost then Soil Decay	-0.37	-0.70	-0.84	-0.61	-0.75	-0.70	-0.84	-0.72
Orchard and Vineyard Trimming	ALT_3 Slash Pile Burn	-0.72	-1.09	-1.20	-0.97	-1.09	-1.02	-1.13	-1.08
	ALT_4 Chip and Spread	-0.35	-0.72	-0.83	-0.60	-0.72	-0.64	-0.76	-0.71
		Net emissions after 100 years, t CO2e / t Biochar							
Wheat Straw	ALT_1 Natural Biomass Decay	-0.91	-2.36	-2.98	-1.76	-2.28	-2.11	-2.64	-2.17
	ALT_2 Compost then Soil Decay	-1.60	-3.05	-3.67	-2.38	-2.90	-2.73	-3.26	-2.78
Orchard and Vineyard Trimming	ALT_3 Slash Pile Burn	-2.98	-3.84	-4.24	-3.52	-3.94	-3.69	-4.11	-4.13
	ALT_4 Chip and Spread	-1.45	-2.53	-2.93	-2.17	-2.60	-2.34	-2.76	-2.71
Wheat Straw	Biochar C efficiency (g BC C / g BM	0.352	0.354	0.354	0.396	0.396	0.396	0.396	0.398
	Biochar C content (g C / g BC)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
	Biomass C content (g C / g BM)	0.435	0.435	0.435	0.435	0.435	0.435	0.435	0.435
Orchard and Vineyard Trimming	Biochar C efficiency (g BC C / g BM	0.400	0.434	0.434	0.450	0.450	0.450	0.450	0.453
	Biochar C content (g C / g BC)	0.81	0.75	0.75	0.80	0.80	0.80	0.80	0.85
	Biomass C content (g C / g BM)	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49

5.2.2.Production Economics

We performed the economic analysis for the four biochar production technologies, each of which was scaled to operate at their maximum economic efficiency. Based on discussions with the technology providers, the minimum number of individual units needed to achieve this level of efficiency was assumed to be 8 flame cap kilns, 5 automated pneumatic-feed gasifiers, 5 automated auger-feed pyrolytic gasifier trains (which fit inside a single container), and 30 high-temperature slow-pyrolysis kilns. All analyses considered the same set of general economic assumptions listed in Table 10, which included costs of \$40/tonne biomass. Also, the costs of emissions control for the two gasifiers and the slow-pyrolysis kiln were included (even though they were not part of the climate impact assessment for the two gasifiers). Analyses for the conversion of two feedstocks, wheat straw and woody trimmings from orchards and vineyards, were performed for each biochar production technology using the feedstock conversion capacities and biochar production efficiencies listed in Table 7. The primary metric calculated in these analyses was the cost per C credit in units of \$ per tonne CO2e.

The estimated C-credit costs for conversion of wheat straw to biochar (Table 12, Fig. 21) ranged from \$434 for the pyrolytic gasifier and high-temperature slow-pyrolysis kiln systems to \$1489 for the flame cap kiln. The pneumatic-feed gasifier C-credit cost was estimated at \$596. Substantially lower C-credit costs were estimated for conversion of woody trimmings to biochar (Table 13, Fig. 22). As before, the pyrolytic gasifier was lowest at \$264, followed by the high-temperature slow-pyrolysis kiln system at \$315, flame cap kiln system at \$409 and pneumatic-feed gasifier at \$411.

Table 12. Economics of carbon credit generation by biochar production from wheat-straw feedstock using four biochar technologies scaled to maximum economic efficiency.

	Maximum Economic Efficiency			
	Wheat-Straw Feedstock			
Cost Description	Manual-Feed Flame Cap Kiln	Automated Continuous-Feed Gasifier	Automated Continuous-Feed Pyrolytic Gasifier	Batch High-Temperature Slow-Pyrolysis Kiln
Capital Expense ↓ Cost per CO2e ($/tonne) →	$ 1,489	$ 596	$ 434	$ 434
Biomass Handling & Preparation				
Walking Floor Trailer, Controls, Bin and Transfer Auger			$ 109,800	
Hammermill (7.5 kW, 0.15 tons/h, 3.25 tonnes/day)	$ 12,678	$ 12,678	$ 47,200	$ 12,678
Briquette Press (2.2 kW, 0.15 tons/h, 3.25 tonnes/day) or Gasifier (7.5 kW, output same)	$ 10,000	$ -	$ 32,100	$ 10,000
Biomass Dryer	$ -	$ -	$ -	$ -
Biomass Conversion	$ 2,900	$ 300,000	$ 169,940	$ 152,214
Emissions Control	$ -	$ 50,000	$ 34,200	$ 20,648
Biochar Cooling and Handling	$ -	$ -	$ 27,280	$ -
Site Footprint (acres/unit)	0.03	0.67	0.60	1.00
Site Acquisition/Development Cost ($/unit)	$ -	$ 16,650	$ 15,000	$ 25,000
Total Capitalization Cost ($/unit)	$ 3,465	$ 51,381	$ 58,993	$ 29,873
Biochar Production Logistics				
Daily Biomass Conversion Capacity/Unit (tonnes)	0.73	1.31	7.26	2.57
Days Operated per Year	180	310	310	310
Annual Biomass Conversion Capacity/Unit (tonnes)	131	405	2250	795
Wheat Acreage to Supply Annual Biomass Need	97	300	1664	588
Orchard/Vineyard Acreage to Supply Annual Biomass Need	654	2029	11270	3985
Apportioned Farm Acreage to Supply Annual Biomass Need	217	673	3739	1322
Biochar Carbon Efficiency (g C in BC/g C in BM)	0.352	0.354	0.396	0.398
Annual Biochar Carbon Production/Unit (tonnes)	20	62	387	138
Biochar Carbon Content (g C/g BC)	0.67	0.67	0.67	0.67
Annual Biochar Production/Unit (tonnes)	30	93	578	206
Number of Units Operated	8	5	5	20
Total Annual Biomass Farmgate Cost ($)	$41,803	$80,993	$449,964	$636,377
Total Annual Biochar Carbon Production (tonnes)	160	312	1936	2757
Carbon Credit Calculations and Expenses				
Annual Project Verification Costs ($)	$ 15,000	$ 15,000	$ 15,000	$ 15,000
CH4 Emissions during Production (g CH4/kg dry biomass)	4.107	0.043	0.073	0.0102
N2O Emissions during Production (g N2O/kg dry biomass)	0.009	0.102	0.185	0.0457
Soot Emissions during Production (g Soot/kg dry biomass)	0.264	0.002	0.125	0.0023
Total Emissions during Production/Unit (tonnes CO2e at 100 y)	184.1	430.1	2555.2	775.6
Biochar Carbon Stored/Unit (tonnes CO2e at 100 y)	64	199	1237	440
CO2e credits per unit biomass (tonnes CO2e/tonne BM)	0.08	0.41	0.28	0.41
CO2e credits per unit biochar (tonnes CO2e/tonne BC)	0.34	1.79	1.10	1.58
Total Net Carbon Credits Generated (tonnes CO2e at 100 y)	82	834	3193	6511
Total Registry Administration Fees ($)	$ 16	$ 167	$ 639	$ 1,302
Transportation Expense				
Diesel fuel per year for biomass transport	$ 194	$ 600	$ 3,333	$ 1,178
Diesel fuel per year for biochar transport	$ 30	$ 92	$ 574	$ 204
Vehicle Cost ($)	$ 100,000	$ 100,000	$ 100,000	$ 100,000
Vehicle Biomass Load Capacity (tonnes)	18	18	18	18
Vehicle Biochar Load Capacity (tonnes)	4	4	4	4
Vehicle Usage (days/year)	0.99	3.07	17.85	6.33
Vehicle Capitalization Cost	$ 43.09	$ 133.94	$ 779.89	$ 276.55
Labor Rate ($/day)	$ 250	$ 250	$ 250	$ 250
Labor	$ 247	$ 766	$ 4,462	$ 1,582
Annual Transportation Cost ($/Unit)	$ 513	$ 1,593	$ 9,149	$ 3,242
Operating Expense				
Labor				
Person-hours/unit/day	2.00	1.67	2.64	6.2
Hourly rate	15	25	25	25
Annual Labor per unit	$ 5,400	$ 12,917	$ 20,460	$ 48,050
Energy				
Electricity (KWh/day)	51.99	144.35	1397.91	255.81
Annual Electricity Use (MWh)	9.36	44.75	433.35	79.30
Annual Electricity Cost ($)	$ 973	$ 4,654	$ 45,068	$ 8,247
Propane (gall/day)	0	1	60.9	39
Annual Propane Use (gall)	0	310	18874	11957
Annual Propane Cost ($)	$ -	$ 505	$ 30,764	$ 19,490
Diesel (gall/day)	0.50	1.31	0	2.57
Annual Diesel Use (gall)	90	405	0	797
Annual Diesel Cost ($)	$ 495	$ 2,227	$ -	$ 4,384
Annual Energy Cost per unit	$ 1,468	$ 7,387	$ 75,832	$ 32,122
Maintenance				
Repair Costs per unit ($)	$ -	$ 10,000	$ 22,494	$ 5,000
Annual Maintenance Cost per unit ($)	$ -	$ 10,000	$ 22,494	$ 5,000
Total Operation Cost per unit	$ 6,868	$ 30,303	$ 118,786	$ 85,172
Total Biomass, Transportation and Operation Cost	$ 100,851	$ 240,472	$ 1,089,641	$ 2,404,641
Adjusted Capitalization Cost	$ 6,214	$ 256,907	$ 294,964	$ 422,318
Total Production Cost	$ 122,081	$ 497,379	$ 1,384,605	$ 2,826,959
Cost per Carbon Credit produced ($/tonne CO2e)	**$ 1,489**	**$ 596**	**$ 434**	**$ 434**

Table 13. Economics of carbon credit generation by biochar production from woody trimmings feedstock using four biochar technologies scaled to maximum economic efficiency.

Cost Description	Maximum Economic Efficiency Orchard and Vineyard Trimmings Feedstock Manual-Feed Flame Cap Kiln	Automated Continuous-Feed Gasifier	Automated Continuous-Feed Pyrolytic Gasifier	Batch High-Temperature Slow-Pyrolysis Kiln
Capital Expense ↓ Cost per CO2e ($/tonne) →	$ 409	$ 411	$ 264	$ 315
Biomass Handling & Preparation				
Walking Floor Trailer, Controls, Bin and Transfer Auger			$ 109,800	
Hammermill (7.5 kW, 0.15 tons/h, 3.25 tonnes/day)	$ -	$ 12,678	$ 47,200	$ 12,678
Briquette Press (2.2 kW, 0.15 tons/h, 3.25 tonnes/day) or Gasifier (7.5 kW, output same)	$ -	$ -	$ -	$ -
Biomass Dryer	$ -	$ -	$ 28,720	$ -
Biomass Conversion	$ 2,900	$ 300,000	$ 169,940	$ 152,214
Emissions Control	$ -	$ 50,000	$ 34,200	$ 20,648
Biochar Cooling and Handling	$ -	$ -	$ 27,280	$ -
Site Footprint (acres/unit)	0.03	0.67	0.60	1.00
Site Acquisition/Development Cost ($/unit)	$ -	$ 16,650	$ 15,000	$ 25,000
Total Capitalization Cost ($/unit)	$ 393	$ 51,381	$ 58,535	$ 28,518
Biochar Production Logistics				
Daily Biomass Conversion Capacity/Unit (tonnes)	0.73	1.31	7.26	2.57
Days Operated per Year	180	310	310	310
Annual Biomass Conversion Capacity/Unit (tonnes)	131	405	2250	795
Wheat Acreage to Supply Annual Biomass Need	97	300	1664	588
Orchard/Vineyard Acreage to Supply Annual Biomass Need	654	2029	11270	3985
Apportioned Farm Acreage to Supply Annual Biomass Need	217	673	3739	1322
Biochar Carbon Efficiency (g C in BC/g C in BM)	0.400	0.434	0.45	0.453
Annual Biochar Carbon Production/Unit (tonnes)	26	86	496	177
Biochar Carbon Content (g C/g BC)	0.81	0.75	0.8	0.85
Annual Biochar Production/Unit (tonnes)	32	115	620	208
Number of Units Operated	8	5	5	20
Total Annual Biomass Farmgate Cost ($)	$41,803	$80,993	$449,964	$636,377
Total Annual Biochar Carbon Production (tonnes)	205	431	2480	3531
Carbon Credit Calculations and Expenses				
Annual Project Verification Costs ($)	$ 15,000	$ 15,000	$ 15,000	$ 15,000
CH4 Emissions during Production (g CH4/kg dry biomass)	4.107	0.043	0.073	0.0102
N2O Emissions during Production (g N2O/kg dry biomass)	0.009	0.102	0.185	0.0457
Soot Emissions during Production (g Soot/kg dry biomass)	0.264	0.002	0.125	0.0023
Total Emissions during Production/Unit (tonnes CO2e at 100 y)	189.8	424.5	2608.4	793.5
Biochar Carbon Stored/Unit (tonnes CO2e at 100 y)	82	275	1585	564
CO2e credits per unit biomass (tonnes CO2e/tonne BM)	0.23	0.60	0.45	0.56
CO2e credits per unit biochar (tonnes CO2e/tonne BC)	0.93	2.11	1.62	2.16
Total Net Carbon Credits Generated (tonnes CO2e at 100 y)	236	1211	5014	8974
Total Registry Administration Fees ($)	$ 47	$ 242	$ 1,003	$ 1,795
Transportation Expense				
Diesel fuel per year for biomass transport	$ 194	$ 600	$ 3,333	$ 1,178
Diesel fuel per year for biochar transport	$ 38	$ 128	$ 735	$ 262
Vehicle Cost ($)	$ 100,000	$ 100,000	$ 100,000	$ 100,000
Vehicle Biomass Load Capacity (tonnes)	18	18	18	18
Vehicle Biochar Load Capacity (tonnes)	4	4	4	4
Vehicle Usage (days/year)	1.10	3.54	20.04	7.11
Vehicle Capitalization Cost	$ 48.02	$ 154.80	$ 875.52	$ 310.59
Labor Rate ($/day)	$ 250	$ 250	$ 250	$ 250
Labor	$ 275	$ 886	$ 5,009	$ 1,777
Annual Transportation Cost ($/Unit)	$ 554	$ 1,768	$ 9,953	$ 3,528
Operating Expense				
Labor				
Person-hours/unit/day	2.00	1.67	2.64	6.2
Hourly rate	15	25	25	25
Annual Labor per unit	$ 5,400	$ 12,917	$ 20,460	$ 48,050
Energy				
Electricity (KWh/day)	0.00	144.35	995.95	255.81
Annual Electricity Use (MWh)	0.00	44.75	308.75	79.30
Annual Electricity Cost ($)	$ -	$ 4,654	$ 32,110	$ 8,247
Propane (gall/day)	0	1	60.9	38.6
Annual Propane Use (gall)	0	310	18874	11957
Annual Propane Cost ($)	$ -	$ 505	$ 30,764	$ 19,490
Diesel (gall/day)	0.50	1.31	0	2.57
Annual Diesel Use (gall)	90	405	0	797
Annual Diesel Cost ($)	$ 495	$ 2,227	$ -	$ 4,384
Annual Energy Cost per unit	$ 495	$ 7,387	$ 62,874	$ 32,122
Maintenance				
Repair Costs per unit ($)	$ -	$ 10,000	$ 22,494	$ 5,000
Annual Maintenance Cost per unit ($)	$ -	$ 10,000	$ 22,494	$ 5,000
Total Operation Cost per unit	$ 5,895	$ 30,303	$ 105,828	$ 85,172
Total Biomass, Transportation and Operation Cost	$ 93,397	$ 241,349	$ 1,028,866	$ 2,410,364
Adjusted Capitalization Cost	$ 3,143	$ 256,907	$ 292,675	$ 417,577
Total Production Cost	$ 96,540	$ 498,256	$ 1,321,541	$ 2,827,941
Cost per Carbon Credit produced ($/tonne CO2e)	**$ 409**	**$ 411**	**$ 264**	**$ 315**

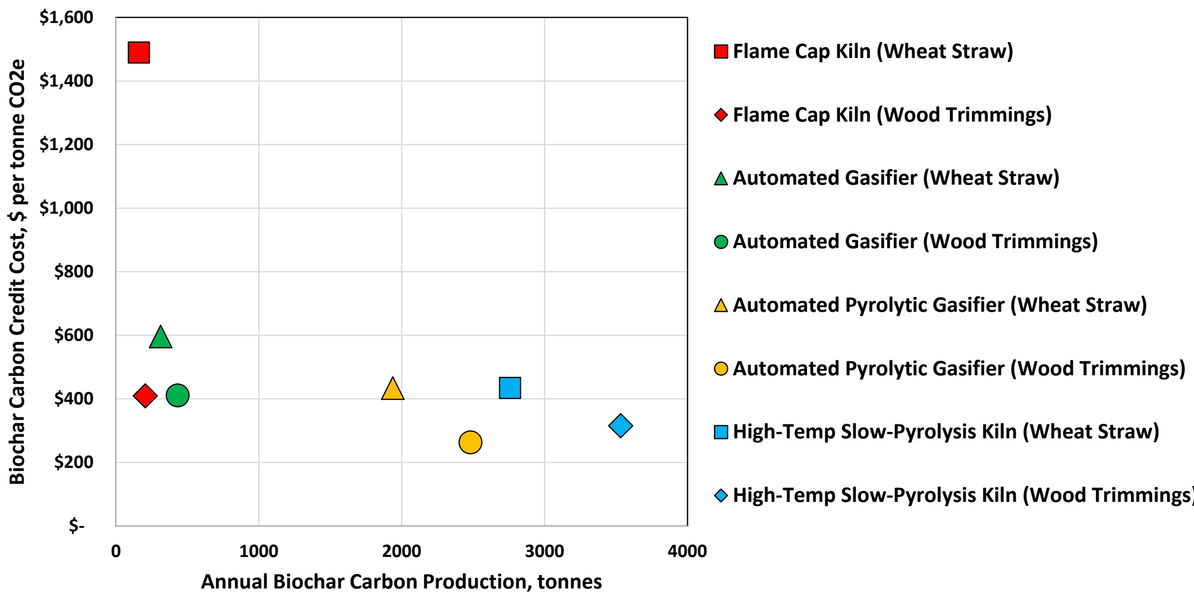


Figure 21. Summary of estimated carbon credit costs associated with the different biochar production scenarios modeled at maximum economic efficiency. Costs are shown for the lowest biochar production levels at which maximum economic efficiency is achieved.

To help understand the factors leading to the overall economic results shown in Tables 12 and 13, and Fig. 21, we extracted the costs associated with capital, biomass acquisition, transportation, labor, energy, and maintenance for the biochar production scenarios (Fig. 22). In the top panels, costs ($ per tonne CO2e) are shown, whereas fractions of the total cost for each category are shown in the bottom panels. For the flame cap kiln, the two dominant cost categories are labor and biomass, each about 40% of the total cost. Capital accounts for 52% of the cost for the pneumatic gasifier, followed by biomass and labor at 16% and 13%, respectively. One-third of the cost for the pyrolytic gasifier is biomass, followed by energy and capital at about 27% and 21%, respectively. Labor is the largest cost category for the slow-pyrolysis kiln system at 34% followed by biomass and energy at 23% and capital at 15%. Maintenance and transportation are consistently the smallest cost categories for biochar production across the four systems analyzed, never exceeding 12% of the total when taken together. The large energy costs for the pyrolytic gasifier and slow-pyrolysis kiln system stem primarily from the use of propane to fuel the afterburners used for emission control. Emission control for the pneumatic gasifier focuses on particulate removal and, when implemented, will be achieved by a high-efficiency cyclone rather than an afterburner.

The primary conclusion drawn from this economic analysis, given these initial model constraints, is that C credits alone (at $100/tonne CO2e) are not sufficient to fund implementation of biochar technology at this scale of production. We next explore potential ways to lower the cost per C credit by combining biochar technology with other approaches. The approaches considered include 1) subsidizing the cost of biomass, 2) using model parameters derived from LCAs to establish how may C credits may be generated, 3) combining biochar production with "in-network" co-composting operations.

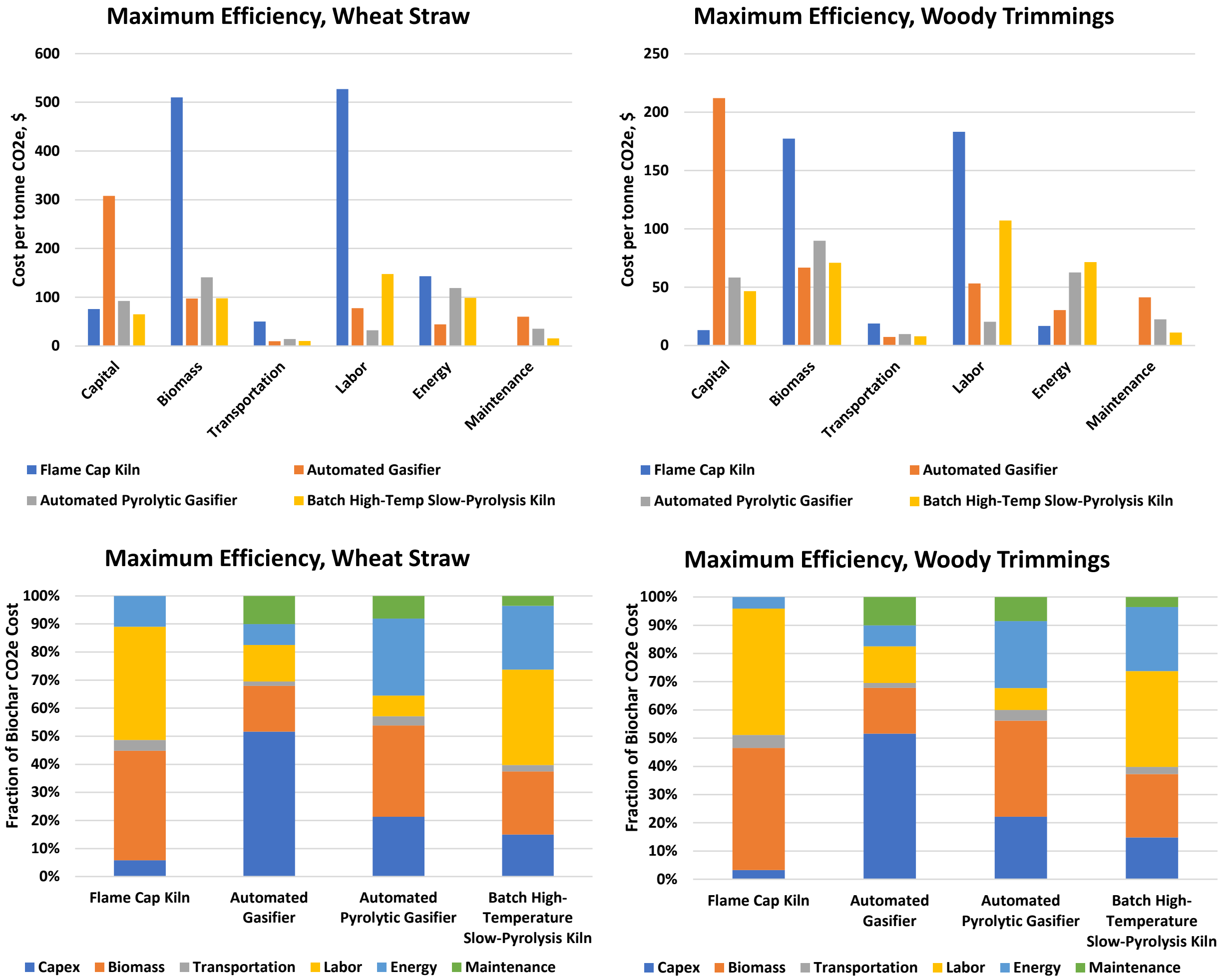


Figure 22. Breakdown of cost factors for the generation of carbon credits by the biochar technologies operating at maximum economic efficiency for conversion of wheat straw and woody trimmings biomass feedstocks.

We explored two types of biomass subsidies—one (S_1a) in which the cost of the biomass is nil, as might apply for a cooperative farm-biochar production operation, and the other (S_1b) in which a tipping fee of $40/tonne of biomass is paid to the biochar production operation to remove the biomass from its source. The results (Table 14) show very large decreases in the cost of a C credit, with that for conversion of woody trimmings falling below the nominal $100/tonne CO2e threshold to $55 for the flame cap kiln and $84 for the pyrolytic gasifier with the tipping fee subsidy.

To assign C credit values using the LCA approach we substituted the C credit production levels provided in the baseline economic analysis (total tonnes CO2e in Tables 12 and 13) with those estimated from our four alternative biomass scenarios used in the climate-impact analysis. Specifically, we took the ratio for each biomass scenario/biochar production method in Table 11 (tonnes of CO2e per tonne of biomass at 100 y) to the comparable baseline value amount for the biochar production method in Tables 12 and 13 (tonnes of CO2e per tonne of biomass at 100 y) and then multiplied the baseline total tonnes of CO2e for that production method in Tables 12 and 13 by this ratio. Substitution of this value for the total tonnes CO2e in Tables 12 and 13 yields four LCA-based estimates of C credit cost for each biochar production method (S_2a, S_2b, S_2c, and S_2d). As with the biomass subsidy scenarios, the results (Table 14) show substantial decreases in the cost of C credits, but none of the production methods yielded costs below $100/tonne CO2e for application of the LCA approach only.

We next explored the effects of the 16 possible combinations of biomass subsidies (S_1x), LCA-based C credit production levels (S_2x), and feedstocks on C credit costs. As one might expect, the results (Table 14) show further decreases in C-credit cost, with 2 out of the 16 free-biomass scenarios (S_2 + S_1a) and 7 of the 16 tipping-fee biomass scenarios (S_2 + S_1b) yielding values less than $100. These low C-credit costs are obtained only for the flame cap kiln and pyrolytic gasifier biochar production methods, however. C-credit costs are lowest for the tipping-fee/woody trimmings feedstock scenarios (S_1b + S_2c and S_1b + S_2d) where they range from $17 to $63. Comparable values for the tipping-fee/wheat-straw feedstock scenarios (S_1b + S_2a and S_1b + S_2b) range from $71 to $95.

In the final stage of our exploration of ways to lower the production cost of C-credits in biochar systems, we estimated the potential C-credit costs associated when biochar (at 10% by dry weight) is mixed with the composting feedstock (at 90% by dry weight) and the mixture then co-composted as part of an existing composting operation. Biochar co-composting operations have been shown to decrease emissions of CH_4 and N_2O (Vandecasteele et al. 2016; Kammann et al. 2017; Liu et al. 2017; Wu et al. 2017; Lyu et al. 2022; Graves et al. 2022) during the composting process. We modeled baseline aerobic composting emissions using the default emission factors from the IPCC (2006) and then considered two alternative levels of CH_4 and N_2O emissions (average and maximum decreases) from incorporation of biochar based on the review of Lyu et al. (2022) to estimate net emission changes in units of tonnes CO2e per tonne biomass *composted*. The model parameters (Table 15) consider average and maximum emission decreases of 15% and 80% for CH_4, and the same 10% decrease for N_2O in both alternatives. The net emission decreases for the two co-composting alternatives were then expressed in terms of the biomass used to make the biochar (i.e., tonnes CO2e per tonne biomass) by multiplying by factors to account for biochar dilution in the co-compost mixture and the amount of biochar produced per unit of biomass for each technology. The cost of biochar incorporation was assumed to be negligible (or subsidized). The same approach taken in the biochar LCA (S_2) calculations was used to assign the total C-credit levels for each production technology.

The results for the two co-composting alternatives (S_3a and S_3b in Table 14) show substantial decreases in the cost per C credit relative to the baseline but no values below $100/tonne are obtained. Application of biomass subsidies, however, yields values below $100/tonne for 7 out of the 16 possible combinations (S_3a + S_1, and S_3b + S_1), 5 of which are when maximum co-composting emission decreases are assumed. Three of the tipping-fee subsidies yield C-credit costs below $50/tonne.

When we explore the 96 possible combinations of the co-composting alternatives (S_3) with the biomass subsidy (S_1) and LCA-derived C credit (S_2) scenarios we obtain the lowest C-credit costs (Table 14). Although the decreases are modest relative to those obtained for the S_1 and S_2 combinations explored earlier, 29 of the 96 scenario combinations yield C-credit costs below $100/tonne CO2e and 8 are below $50/tonne CO2e (Table 14). Of the 29 low-cost scenarios, 9 are for wheat straw biochar feedstock, 20 for woody trimming biochar feedstock, 24 are associated with the flame cap kiln or the pyrolytic gasifier biochar production methods and 5 with the high-temperature slow-pyrolysis kiln method. For wheat straw feedstock, the lowest C-credit costs for each biochar production technology are obtained for the S_3b + S_2b + S_1b scenario combination. For woody trimmings feedstock, the lowest C-credit costs for each biochar production technology are obtained for the S_3b + S_2c + S_1b scenario combination.

We identified but did not evaluate two other scenario classes that could be considered to decrease the cost of C credits using these biochar production methods (Table 14). These include S_4, selling a portion of the biochar production “out-of-network” rather than retaining all for grower/producer use, and S_5, using waste heat and CO2 from biochar production to supplement greenhouse operations and enhance weathering of Ca- and Mg-bearing silicate rocks.

Table 14. Estimated cost of CO2e for four biochar production technologies under scenarios that include biomass subsidies (S_1), LCA-supported C Credits (S_2), or both (S_2 + S_1). An additional set of LCA-supported scenarios is given for combining co-composting of biochar (S_3, cost subsidized) with the production credits (S_2). Two additional scenarios requiring development are also listed. Light green cells highlight values between nominal CO2e costs of $50 to $100/tonne, dark green cells highlight values below nominal CO2e costs of $50/tonne.

Maximum Economic Efficiency	Wheat-Straw Feedstock				Orchard and Vineyard Trimmings Feedstock			
Economic Scenario	Manual-Feed Flame Cap Kiln	Automated Continuous-Feed Gasifier	Continuous-Feed Pyrolytic Gasifier	Temperature Slow-Pyrolysis Kiln	Manual-Feed Flame Cap Kiln	Automated Continuous-Feed Gasifier	Continuous-Feed Pyrolytic Gasifier	Temperature Slow-Pyrolysis Kiln
	CO2e Cost, $/tonne				CO2e Cost, $/tonne			
Baseline	1489	596	434	434	409	411	264	315
S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	979	499	293	336	232	344	174	244
S_1b: Tipping Fee ($40/t)	469	402	152	239	55	278	84	173
S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	564	452	272	317	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	319	350	201	247	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	128	226	121	165
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	264	343	196	251
S_2 + S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	371	379	184	246	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	210	293	136	191	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	73	189	80	128
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	150	288	129	195
S_2 + S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	178	305	95	174	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	101	236	71	136	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	17	153	39	91
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	35	232	63	138
S_3: "In-Network" Co-composting Operation								
S_3a: Average Aerobic Co-Compost Emission Decrease	844	520	350	372	311	361	223	277
S_3b: Maximum Aerobic Co-Compost Emission Decrease	348	366	215	254	174	257	148	199
S_3a + S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	555	435	236	289	176	302	147	215
S_1b: Tipping Fee ($40/t)	266	351	123	205	42	243	71	152
S_3a + S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	438	407	237	283	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	274	322	181	226	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	117	210	112	154
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	219	307	173	227
S_3a + S_1 + S_2: Carbon Credits based on LCA								
S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	288	341	160	219	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	181	270	122	175	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	66	176	74	119
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	124	257	114	176
S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	138	274	83	155	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	87	217	63	124	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	16	142	36	85
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	29	207	55	125
S_3b + S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	229	307	145	197	98	215	97	154
S_1b: Tipping Fee ($40/t)	110	247	75	140	23	173	47	109
S_3b + S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	252	306	166	209	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	188	256	137	176	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	90	170	89	126
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	141	229	124	171
S_3b + S_1 + S_2: Carbon Credits based on LCA								
S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	166	256	112	162	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	124	214	92	136	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	51	142	59	98
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	80	192	82	133
S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	80	207	58	115	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	59	172	48	97	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	12	115	28	69
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	19	154	40	94
S_4: Biochar Sales "Out-of-Network"								
	--	--	--	--	--	--	--	--
S_5: Use of Waste Heat and CO2								
S_5a: Greenhouse Operations	--	--	--	--	--	--	--	--
S_5b: Enhanced Rock Weathering	--	--	--	--	--	--	--	--

Table 15. Model parameters for baseline and alternative compost emission scenarios used in life cycle assessment of impact of biochar co-composting.

Model Parameter	Units	Aerobic Compost Scenarios (Wood/Straw)		
		No Biochar	Co-Composting with 10% Biochar	
		Baseline	ALT_1: Average Emission Decrease	ALT_2: Maximum Emission Decrease
C content of biomass	kg C / kg dry biomass	0.503	0.503	0.503
Compost decay rate	half-life, yr	0.44	0.44	0.44
Compost C efficiency	kg compost C / kg biomass C	0.5	0.5	0.5
C content of mature compost	kg compost C / kg compost	0.326	0.326	0.326
CH_4 emission factor	g CH_4 / kg dry biomass	10	8.5	2
N_2O emission factor	g N_2O / kg dry biomass	0.6	0.54	0.54

The final portion of our economic assessment focuses on matching the density of available biomass at the county level with the production levels of the four biochar technologies to obtain an idea of the transportation radius associated with each biomass conversion facility type. We calculated the supply radius, R (miles), for a biomass conversion facility assuming an even distribution of biomass in the county cropland using

$$R = \alpha*(\text{BCF capacity})^{0.5},$$

where $\alpha = 1/(640*\pi*\rho)^{0.5}$ is the areal scaling coefficient, ρ is the biomass density in dry tonnes / cropland acre, and the BCF capacity is the biomass conversion capacity of the facility (dry tonnes / year). Values of α and ρ for each county are shown in Table 16.

The results in Table 16 show that four contiguous counties in the northern Willamette Valley (Marion, Polk, Washington, and Yamhill) can supply 80% of the biomass resource, with another 11% of the biomass being supplied by the southernmost county (Lane). The relatively high biomass densities of these five counties suggest that they offer the best locations for economically efficient production of biochar.

Table 16. County-level analysis of the biomass density per cropland acre to arrive at an areal scaling coefficient for transportation distance per tonne of biomass supplied. Note that biomass data are metric tonnes, rather than tons.

County	Land in Farms, acres	Fraction of Farmland that is Cropland	Cropland, acres	Total Biomass Resource, dry tonnes	Biomass density (ρ), dry tonnes / cropland acre	Power Law Coefficient (α), miles / tonne$^{0.5}$
Benton	127626	0.54	68918	628	0.0091	0.2337
Clackamas	157426	0.53	83436	1118	0.0134	0.1927
Lane	203148	0.48	97511	11780	0.1208	0.0642
Linn	314947	0.77	242509	5243	0.0216	0.1517
Marion	288671	0.82	236710	25725	0.1087	0.0676
Multnomah	25435	0.61	15515	1698	0.1095	0.0674
Polk	148905	0.72	107212	17876	0.1667	0.0546
Washington	104715	0.72	75395	17570	0.2330	0.0462
Yamhill	169357	0.67	113469	19221	0.1694	0.0542
Totals:	**1540230**	**0.676**	**1040675**	**100858**	**0.1058**	

Using the equation given previously, we calculated the mean supply radius for the 9 counties in the Willamette Valley as a function of biomass conversion facility capacity. The results (Fig. 23) show a transportation radius of 5-7 miles will provide 90% of the available biomass (i.e., that in the five counties having high biomass density) to the largest capacity conversion facilities. Maximum efficiency for the high-temperature slow-pyrolysis kiln is achieved with a 30-kiln array (ca. 8000 dry tonne biomass / year capacity); doubling of this capacity to a 60-kiln array (ca. 16,000 dry tonne biomass / year) would be expected to yield the same efficiency.

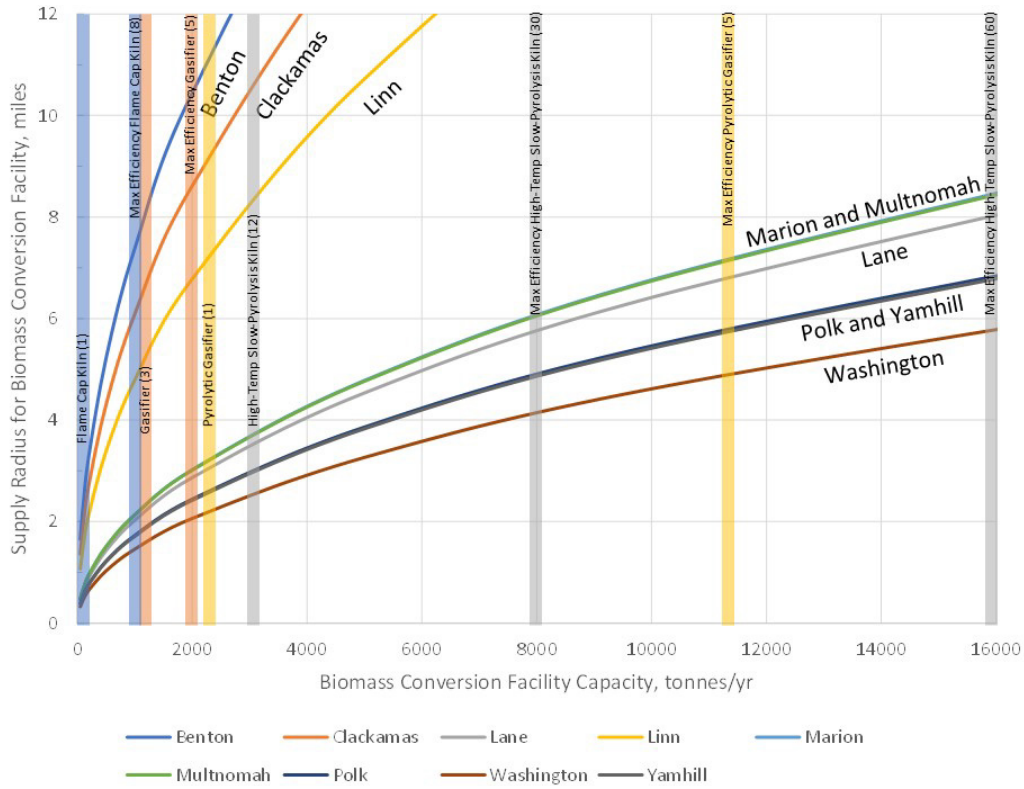


Figure 23. Scaling of biomass supply radius (miles) as biomass conversion facility capacity (dry tonnes/year) increases for counties in Willamette Valley region. Facility capacities for specific conversion technologies are shown as vertical bars.

6. Summary, Recommendations and Path Forward

In the five major sections preceding this one we provide an overview and technical assessment of the viability of the biochar technology approach when implemented at the small-scale in the PNW of the USA. Here we summarize each of the five sections and then continue with our recommendations and a discussion of the potential path forward.

6.1. Summary

In *Section 1*, we review expected changes in the climate of the PNW by 2100, the impacts of which include more frequent summer droughts and heat waves coupled with decreases in the availability of water for late summer irrigation. We list the GWPs of the major GHG/As associated with biochar technology (CO_2, CH_4, N_2O, and soot), show how they change over the course of 100 years after emission, and how they are used to express the climate impact in terms of CO2e. We give a brief overview of the importance of small-scale agriculture operations to rural economies and list the challenges they face, which include limited availability of labor and expertise, low access to capital, and a disproportionately small share of public financial support, all leading to increases in their financial risk. We conclude with high-level introductions to biochar technology and C-offset mechanisms and list the overall goal of the work which is to evaluate the state of biochar technology and determine the feasibility of integrating small-scale biochar production in ways that benefit smaller, diversified producers.

In *Section 2*, we provide an in-depth evaluation of the aspects of biochar technology having the most relevance to small-scale agricultural operations in the PNW. These aspects include the types of feedstocks (we focus on crop residues produced on-farm rather than woody biomass from forestry operations or purpose-grown biomass crops), and the methods associated with their harvest and pretreatment for biochar production. Potential feedstock pretreatments include comminution and pelletization to provide the optimum biomass handling properties and heat/mass transfer rates for the biochar production process being used. Drying is generally not needed for cereal straw biomass, but important for woody biomass.

We then review the most important aspect of biochar technology, the method of production. Of the wide variety of types and scales of production available, we identify four small-scale systems, portable flame-cap kilns, high-temperature slow-pyrolysis kilns, automated pneumatic-feed gasifiers, and automated auger-feed pyrolytic gasifiers, as the most relevant to use by small agricultural operations. Of these, flame-cap kilns are the simplest and least capital intensive but are labor-intensive and less likely to yield a consistent biochar product. The other three methods yield consistent biochar quality and are highly automated.

We follow with brief discussions of the tradeoffs associated with capturing bioenergy released during biochar production and a survey of the different ways in which biochar can be applied to soils, before concluding with short assessments of the potential for integration of biochar production with other technologies such as composting, greenhouse/nursery operations, enhanced rock weathering, hydrothermal carbonization, anaerobic digestion, and small-scale farming. Of these technologies, we assess that integration with composting, greenhouse/nursery operations, and enhanced rock weathering have the greatest promise for small-scale biochar production in the PNW. Integration with small-scale farming shows great promise where capital resources are limited and farm labor is relatively plentiful but successful integration in the PNW, where these conditions are not present, will depend largely on the market value of C offsets and the ability to meet environmental permitting requirements.

In *Section 3*, we introduce the tools needed to assess the potential climate impact of biochar technology when implemented in the PNW. First, we present information about the available biomass, energy infrastructure, and soil resources. Within the agricultural sector, 70% of the available biomass is in the form of crop residues (dominantly wheat straw), 13% is orchard and vineyard residues (woody biomass from trimmings), and 17% is manure from large dairy operations. The amount of biomass available is moderately sensitive to price, with a 23% increase in harvestable quantities of wheat straw for a doubling of biomass market price (from \$50/dry ton biomass to \$100/dry ton). Substantial quantities of woody biomass are also available from forestry residues at \$100/dry ton whereas none is available at \$50/dry ton. With respect to energy, the large hydropower capacity in the PNW decreases the C intensity of the primary energy supply and, most notably, that of the electrical grid supply where C intensities are only 27-38% of the average for the US. Replacement of grid electricity by bioenergy thus is impractical in the PNW. Replacement of thermal energy derived from combustion of natural gas or fuel oil, however, is comparable to that of the rest of the US where C credits of \$100/ton CO2e provide a premium of 44% to 62% of the baseline cost of the thermal energy. The soil resource in the PNW is vast. At full biochar production rates, the agronomic soils in the region can accommodate maximum levels of biochar amendments for many decades before development of other biochar storage locations is needed.

We next introduce the concept of a time-sensitive LCA, which allows calculation of the C payback period for different combinations of biochar technology and alternative biomass fates. We develop a detailed hypothetical LCA example for wheat-straw feedstock to show how the factors involved in the three stages of biochar production (biomass harvest and preparation, thermochemical conversion to biochar and bioenergy, and biochar post-treatment and storage in soil) combine to yield different climate outcomes relative to the alternative biomass fates of decay in soil or compost followed by soil decay. Nine implementations of biochar technology are assessed and the results show that the best climate impacts are obtained from biochar technologies having high C efficiency and biochar quality combined with post-conversion co-composting and enhancement of crop productivity.

We conclude this section with a brief overview of the environmental impacts of other aspects of biochar technology including the potential for production of dioxins, PAHs, and VOCs. Formation of dioxins and PAHs at levels leading to environmental concern during biochar production is unlikely in modern biochar production methods. Flame-cap kilns may generate PAHs in some instances due to operator error, but even if generated, strong sorption of PAHs to biochar decreases the environmental risk. However, the release of VOCs from biomass during storage and pre-treatment is of concern and can be mitigated by collocating pre-conversion processing operations and biochar production facilities where the latter can destroy the VOCs released from the biomass.

In *Section 4*, we introduce C-offset crediting, discuss the Verra and Puro.Earth C-crediting mechanisms for biochar in some detail, explore some of the technical gaps that affect pricing/quality of biochar C credits and then briefly discuss C credits associated with applications of biochar technology to other C-offset technologies. Critical technical gaps include an early lack of scientific consensus on the longevity of biochar C in soils stemming mainly from the variety of feedstocks and processes by which biochar is made, and similar concerns about the C efficiency and GHG/A emissions of biochar production processes. A consensus on the impact of biochar amendments on npSOM is in the early stages and this suggests that biochar increases npSOM in agronomic soils substantially on a decade-to-century time scale.

We conclude by discussing the potential revenue streams for biochar C credits now and in the future. Price forecasts for C credits vary widely depending on the assumptions made. Two scenarios predict C credit values of \$200 per tonne CO2e by 2030, whereas a third scenario focused on the voluntary market suggests very modest increases in C credit value until 2050 when levels of about \$50 per tonne CO2e are reached. We show how project size can affect fees associated with registration using Verra's fee schedule as an example. In the example, projects smaller than 10,000 tonnes CO2e are charged \$0.17 per tonne CO2e and the maximum registration fees of \$0.26 per tonne CO2e are seen at projects between 10,000 and 100,000 tonnes CO2e. These fees drop exponentially back to \$0.17 per tonne CO2e at 1 million tonnes of CO2e and then continue to decrease before stabilizing at \$0.03 per tonne CO2e for projects larger than 10 million tonnes of CO2e.

In *Section 5*, we consolidate the information presented in the preceding sections to develop a range of scenarios that assess the climate impact and economic costs of four specific biochar production technologies applied to two feedstocks. First, we use USDOE models of crop residue availability and USDA geographic information and statistics about farm size to select the Willamette Valley region of Oregon, which has a high proportion of small farms and a relatively low density of biomass production, for further analysis of biochar economic viability. The annual biomass production in this 9-county region is about 111,000 dry tons, 78% of which is wheat straw and 22% woody trimmings from orchard and vineyard operations. This biomass can support 50 to 200 biomass conversion facilities of the size envisioned in this report. For the wheat-straw and woody trimmings biomass feedstocks, we select the following four biochar production technologies for detailed study due to the availability of climate impact and economic information:

- a manual-feed flame cap kiln (e.g., Ring-of-Fire kiln, Wilson Biochar Associates, https://wilsonbiochar.com/),
- a containerized automated pneumatic-feed gasifier system (Qualterra, https://qualterraag.com , formerly a division of NuPhY, which acquired Ag Energy Systems),
- a containerized automated auger-driven pyrolytic gasifier system *without* an optional afterburner for emissions control (Advanced Renewable Technology, International, ARTi, https://www.arti.com/), and
- a batch, computer-controlled high-temperature slow-pyrolysis kiln system with a propane afterburner for emissions control (Biochar Now, https://biocharnow.com/).

Because the two gasifier systems can also generate bioenergy, and there are two possible emission configurations for the ARTi system, we model a total of eight biochar production scenarios for each feedstock type, 1 each for flame-cap kilns and high-temperature pyrolysis kilns, 2 for the Qualterra gasifier, and 4 for the ARTi gasifier. The biochar production variables we consider include C contents of biomass and biochar, C efficiency of the process, biochar C decay rate in soil, emission factors for CO_2, CH_4, N_2O and soot, and a fossil-C offset factor that combines fossil-C emissions during the process with fossil-C offsets when bioenergy is generated. We also identify two alternative biomass scenarios for each feedstock, natural biomass decay in soil and composting followed by biomass decay in soil for the wheat straw, and slash-pile burn and chipping and spreading for the woody trimmings.

To assess the economics of the biochar production methods we focus on the cost of generating C credits ($ per tonne CO2e). Initially, we consider only 4 scenarios for each feedstock, ignoring the economics of bioenergy production or alternative emission control configurations (i.e., using the “standard” emission-control configurations described in the bulleted list directly above) or the benefits of an LCA. Later, we add the LCA approach to calculate C credits that account for the difference between the biochar production route and the alternative fates of the feedstock biomass. We incorporate a broad range of financial information including a fixed-charge rate to annualize capital expenditures, costs of fuel, energy, and transportation, fossil-fuel emission factors and 100-year GWPs, and the biochar decay rate at the temperature of typical Willamette Valley soils. For biomass economics we also consider three alternatives, a cost of $40/tonne, or subsidies to make the biomass either free or worth a $40/tonne tipping fee.

We present time-sensitive climate impacts first and these show that the three modern biochar production methods achieve C-negative net emissions (i.e., a C payback period) within 10 years for all combinations of feedstock, bioenergy, and emission-controls. Of these, the pneumatic-feed gasifier and the high-temperature slow pyrolysis system perform nearly identically and yield the most favorable net emissions due in large part to their very clean GHG/A emission profiles. The flame-cap kiln performs less well, mainly due to its GHG/A emission profile, and achieves C negative net emissions after 26 to 47 years for three of the four feedstock/alternative fate scenarios. The only scenario in which the flame-cap kiln performs sustainably is when the feedstock consists of woody trimmings and the alternative biomass fate is slash-pile burning.

With respect to economics of C credit production, production of credits from wheat straw is considerably more expensive than from woody trimmings due in large part to the lower biomass C content of the feedstock. In the absence of LCA considerations (i.e., the default C credit value in current methodologies), the auger-feed pyrolytic gasifier and high-temperature slow-pyrolysis kiln system yield the least expensive cost for both feedstocks ($434 for wheat straw and $264 to $315 for woody trimmings), followed by the pneumatic-feed gasifier ($596 and $411, respectively) and the flame-cap kiln ($1490 and $409, respectively). The very high costs for wheat straw with the flame-cap kiln are due to the assumed need to pelletize the wheat straw to optimize production with minimal GHG/A emissions. On the other hand, biomass pre-treatment with this kiln for woody trimmings is minimal compared to that for the modern biochar production methods and that accounts for its more competitive cost with that feedstock.

We break down the economic costs for each biochar production method in terms of capital, biomass acquisition, transportation, labor, energy, and maintenance. For the flame cap kiln, the two dominant cost categories are labor and biomass, each about 40% of the total cost. Capital accounts for 52% of the cost for the pneumatic gasifier, followed by biomass and labor at 16% and 13%, respectively. One-third of the cost for the pyrolytic gasifier is biomass, followed by energy and capital at about 27% and 21%, respectively. Labor is the largest cost category for the slow-pyrolysis kiln system at 34% followed by biomass and energy at 23% and capital at 15%. Maintenance and transportation are consistently the smallest cost categories for biochar production across the four systems analyzed, never exceeding 12% of the total when taken together. The large energy costs for the pyrolytic gasifier and slow-pyrolysis kiln system stem primarily from the use of propane to fuel the afterburners used for emission control. Emission control for the pneumatic gasifier focuses on particulate removal and, when implemented, will be achieved by a high-efficiency cyclone rather than an afterburner.

The above costs assume a biomass price of $40/dry tonne and under those circumstances none of the biochar production methods achieves a C-credit cost of production that can be offset by a C credit price of $100/tonne CO2e. When we explore the impacts of biomass cost subsidies, however, this situation improves. With woody trimmings and $40/tonne biomass tipping fees, both the flame-cap kiln and the auger-feed pyrolytic gasifier achieve C credit production costs below $100/tonne CO2e in the absence of LCA considerations. When LCAs that consider the alternative biomass fates are included, the costs decrease further for these two production methods and reach a minimum of $17 for the flame-cap kiln and $39 for the auger-feed pyrolytic gasifier when slash-pile burning is the alternative fate. Given the trends towards elimination of slash-pile burning to protect air quality, a forward-looking alternative for comparison is that of chipping and spreading of the woody trimmings and this approach yields C credit costs with a tipping-fee subsidy of $40/dry tonne biomass of $35 and $63, respectively.

Further reductions in the cost of C credit generation are seen when integration of biochar co-composting as a post-production step before soil amendment is included. In this situation, 30% of the possible scenarios yield C credit production costs below $100/tonne CO2e again primarily with the flame-cap kiln and auger-feed pyrolytic gasifier systems. Only 5 instances below $100/tonne CO2e are seen for the high-temperature slow-pyrolysis kiln system and none for the pneumatic-feed gasifier system, for which the lowest C-credit production cost is $115 with maximum aerobic co-composting offsets, slash-pile burning alternative, and $40/dry tonne biomass tipping fees.

6.2. Recommendations and Path Forward

The combined results of our climate-impact and production-cost analysis show that, as currently configured, none of the four biochar production technologies can sustainably deliver C credits at a nominal price point of $100 / tonne

CO2e without subsidies for the cost of biomass or the use of an LCA-based approach to value C credits. When these two conditions are met, however, one biochar production technology, auger-driven pyrolytic gasification, is viable for use with the small farming systems of interest to this project. Two other modern biochar production technologies, a pneumatic-feed gasifier and a high-temperature slow-pyrolysis kiln system, yield excellent climate impacts but, in their current configurations, remain more expensive to implement. All three technologies can readily scale to larger capacity by adding additional modules, but the current scale at which maximum economic efficiency is achieved seems ideal for a locally based biochar production capability with a transportation radius of 5 to 9 miles.

The fourth technology considered, the flame cap kiln, while viable economically with respect to 100-year C-credit criteria, yields C-payback periods substantially longer than a decade for three of the four alternative biomass scenarios and thus is not considered fully sustainable for these scenarios. Very few emission datasets are available, and results depend heavily on the skill of the operator. Flame cap kiln technology, therefore, seems to be a niche technology best suited for use on small, ad hoc projects in remote locations where woody biomass is the feedstock and slash pile burning is the primary alternative biomass pathway.

Our analysis suggests that the best way to decrease the production cost of C credits is to subsidize the cost of the biomass, either by offering it for free or by paying tipping fees to the biochar producer to dispose of the biomass. A cooperative business model involving collection and donation of the biomass to a central facility in return for receipt and incorporation of an equivalent amount of biochar produced by that biomass also might work in some instances. Combining biomass subsidies with an LCA-derived C-credit valuation brings costs down substantially, in many instances to less than $50/tonne CO2e. Production of C credits using biochar at these cost levels could result in a paradigm shift that would lead the way for widespread adoption of biochar technology at these scales of production. We recommend further analysis be given to these approaches to determine how best to advance the concept.

Identification of $100 / tonne as the nominal price point for C credits may in fact be undervaluing the market. The USEPA is in the process of revising its estimate of the social cost of greenhouse gas emissions upwards (USEPA 2022). Values suggested for CO_2 emissions in 2020 range from $120 to $340 per tonne, depending on the Ramsey discount rate applied. A middle-of-the-road Ramsey discount rate of 2.0% yields $190 per tonne of CO_2. Much higher values are obtained per tonne of CH_4 and N_2O. Widespread adoption of these proposed social cost guidelines by the voluntary C markets would provide a strong foundation for expansion of biochar technology.

Other potential income streams, such as energy production (electrical and/or thermal), integration with composting operations, priming of soil organic matter, and payments for ecosystem services such as improved flood control due to larger water-holding capacities, improved air quality from avoidance of open burning, and wildfire mitigation through fuel reduction, warrant further exploration. Integration with composting operations seems to have great potential, both from an economic standpoint and from that of climate impact. This integration is common for biochar producers in California (e.g., https://pacificbiochar.com/pacific-biochar-biological-activation-process-to-improve-biochar/), but details of the overall economics and climate impact are not widely available. Our analysis suggests that additional C-credit value (lower production cost) may be obtained from the incorporation of a biochar co-composting operation into the cooperative biochar production cycle. This could also yield a more valuable soil amendment for the agricultural producers. We recommend research to understand and perfect the best ways of accomplishing this impact while retaining economic viability. Similarly, priming of soil organic matter in different soils and over long periods is not fully understood. Since soil organic matter tends to reach equilibrium in a matter of a few decades after perturbation, increases in soil carbon stocks stimulated by biochar amendments could provide significant income potential early in the project.

An expense currently not considered in the economic model is that of meeting local air quality regulations. In addition to emission factor determinations for a wide range of pollutants, certified testing for which may cost on the order of $25,000, there is the indirect cost associated with working the permit request through the appropriate authorities. Some of this burden can be absorbed by the manufacturer (e.g., baseline testing of the conversion machine) but the smaller the biomass conversion capacity, the more likely that cost must be borne locally. Flame cap kilns in particular may be difficult to permit.

From an agricultural perspective, we expect that C credits will be the vehicle that pushes biochar into the mainstream. Reliance on enhanced crop yields or water storage capacities may work in special instances, but in general, this reliance is neither sufficient nor profitable at almost any price for biochar, to be the main reason farmers adopt the practice. If C credits are available and sufficiently valued, all that needs to be shown is that storing biochar in agricultural lands does no harm to yields. Enhanced yields and more plant-available water storage may occur but should be considered as a bonus rather than as a regular feature in the overall farm economy.

Lastly, work needs to be done to develop the C-credit marketing protocols to provide full and accurate accounting of the climate impacts of biochar. We have identified and illustrated how the single emission pulse approach underestimates net emissions for long-term projects that have repeated annual emissions. Exclusion of soot emissions from C-crediting calculations also significantly underestimates the warming impact of biochar production, particularly those without effective pollution-control systems.

We have identified several viable biochar production scenarios where integration with adjacent technologies (see Section 2.5), such as compost operations or greenhouses, would result in deeper greenhouse gas reductions. We recommend C registries incentivize these sorts of synergistic facilities by allowing projects to establish a baseline and calculate net emissions reductions (i.e., quantify a project's C credits) using a greenhouse gas boundary that includes the footprint of these adjacent technologies when they are collocated with biochar operations. This approach would more accurately represent climate impacts from these integrated systems and facilitate creative projects that are more cost competitive given the opportunities for deeper greenhouse gas abatement. This sort of integrated LCA approach also applies to baseline emissions scenarios, where biomass feedstocks are likely to emit significant greenhouse gases through combustion and decomposition. We commend Verra and Puro.Earth for allowing projects to establish a "positive" emissions baseline where strong research supports those assumptions and recognize that in many cases, biochar projects are only economical if those positive emissions sources are incorporated into a C-credit calculation. Further peer reviewed LCA analysis for common biochar feedstocks would greatly support incorporation of these important emissions sources into C-credit quantification.

Future methodologies should also consider creating a technology standard that only credits biochar projects produced from operations with a C-payback period of less than 10 years. This will require publication in peer-reviewed journals, as well as robust LCA data based on actual emissions, to gain the traction that is needed. Some LCA-based exploration of how best to separate the net climate benefits of biochar-use from biochar-production is also needed to further expand the options in the C-credit marketplace. To facilitate these recommendations, we also advise registries to periodically integrate a broader set of default values into their methodologies that give more certainty to developers about how to quantify credits based on common biomass sources, technologies, and adjacent operations. Rather than relying on static methodologies where projects must establish new parameters for each new project, integrating default values where strong research exists will allow for more replicable project designs and create a virtuous cycle between biochar research and the C markets that can help biochar production scale.

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Appendix A: Repeated Annual Net Emission Results

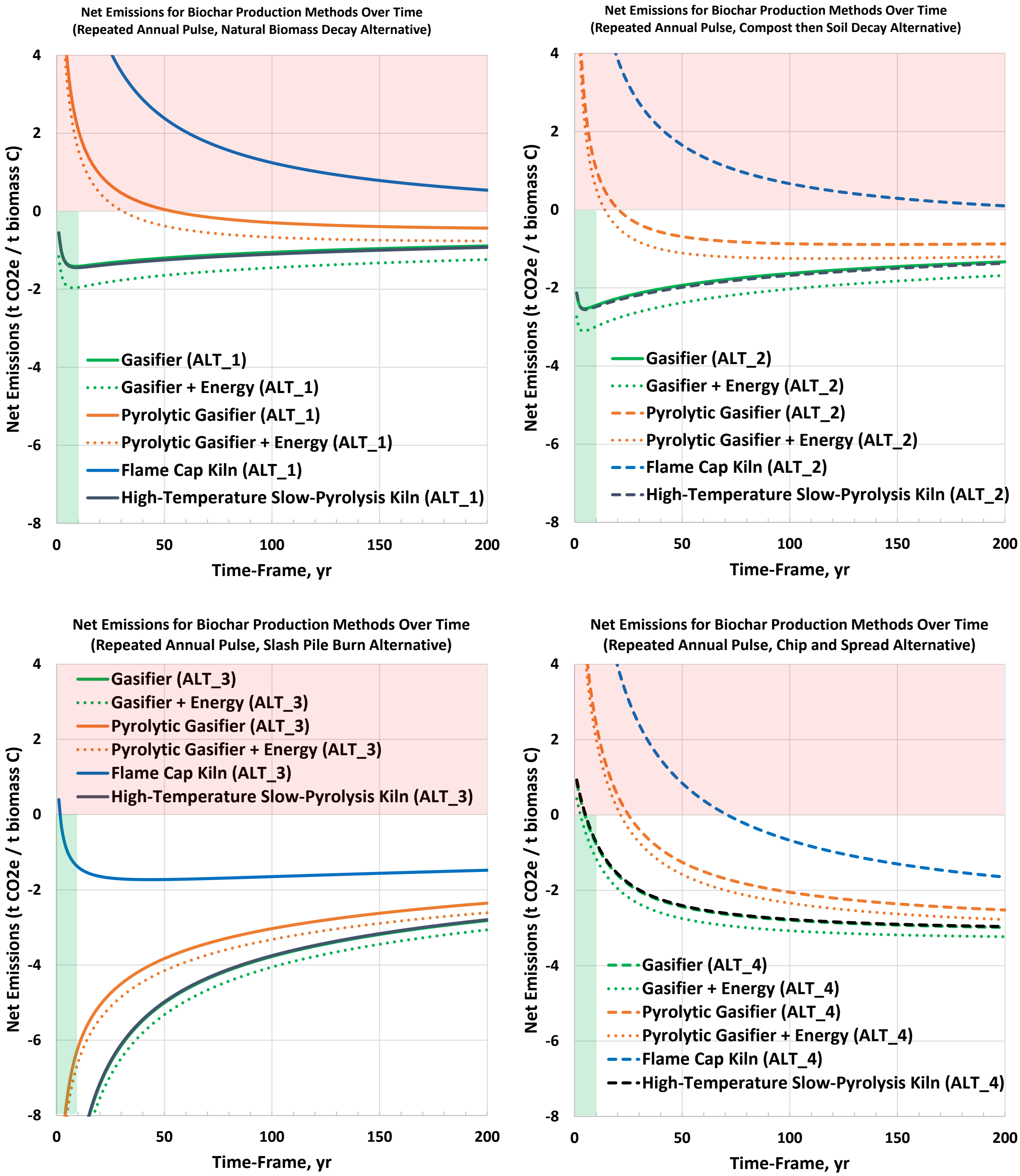

Figure A-1. Net emission curves for repeated annual biochar production pulses for wheat straw (top panels) and woody trimmings (bottom panels) for each of the four alternative biomass pathways. Curves for the addition of energy capture capabilities by the two gasifiers are also shown.

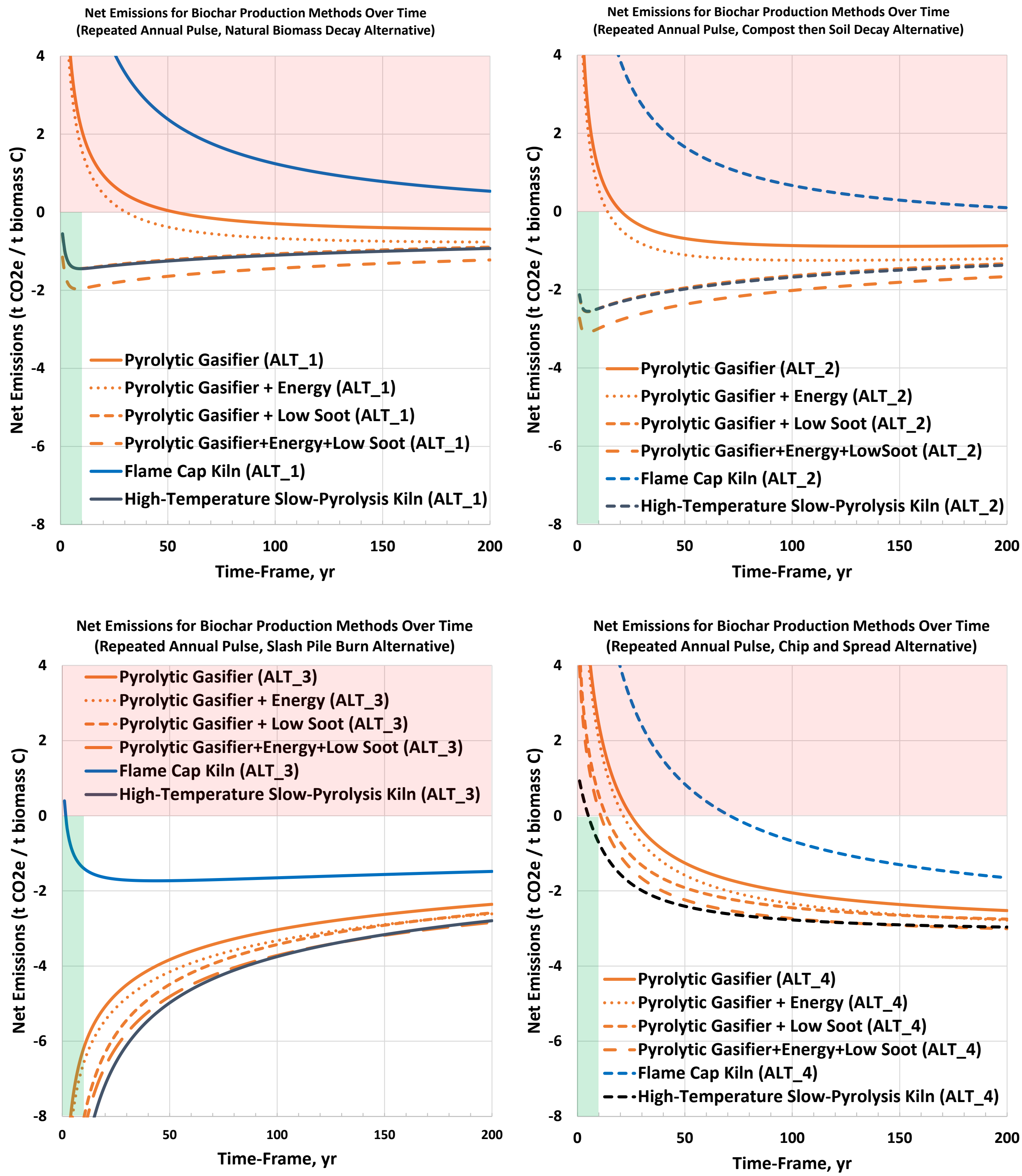

Figure A-2. Net emission curves for single-year biochar production pulses for wheat straw (top panels) and woody trimmings (bottom panels) for each of the four alternative biomass pathways and three of the four biochar production technologies. For the pyrolytic gasifier, curves for the addition of energy capture, soot removal, and both capabilities are also shown.

Table A-1. Carbon payback periods (time needed to attain carbon negativity) and net emissions after 100 years for different combinations of biomass conversion technology, feedstock, and alternative biomass path assuming repeated annual production pulses.

		Repeated Annual Pulses							
Biomass Conversion Technology		Flame-Cap Kiln	Gasifier	Gasifier w/Energy	Pyrolytic Gasifier	Pyrolytic Gasifier w/Energy	Pyrolytic Gasifier w/Low Soot	Pyrolytic Gasifier w/Energy w/Low Soot	Slow Pyrolysis Kiln
Feedstock	**Alternative Biomass Path**	Carbon Payback Period, years							
Wheat Straw	ALT_1 Natural Biomass Decay	200	0	0	53	30	0	0	0
	ALT_2 Compost then Soil Decay	200	0	0	20	14	0	0	0
Orchard and Vineyard Trimming	ALT_3 Slash Pile Burn	1	0	0	0	0	0	0	0
	ALT_4 Chip and Spread	70	4	2	25	21	13	10	5
		Net emissions after 100 years, t CO2e / t Biomass C							
Wheat Straw	ALT_1 Natural Biomass Decay	1.24	-1.05	-1.45	-0.29	-0.67	-1.07	-1.44	-1.10
	ALT_2 Compost then Soil Decay	0.66	-1.63	-2.03	-0.87	-1.25	-1.64	-2.02	-1.68
Orchard and Vineyard Trimming	ALT_3 Slash Pile Burn	-1.65	-3.77	-4.05	-3.03	-3.32	-3.43	-3.71	-3.75
	ALT_4 Chip and Spread	-0.67	-2.79	-3.08	-2.05	-2.34	-2.45	-2.74	-2.77
		Net emissions after 100 years, t CO2e / t Biomass							
Wheat Straw	ALT_1 Natural Biomass Decay	-0.72	-1.64	-1.76	-1.32	-1.45	-1.49	-1.62	-1.63
	ALT_2 Compost then Soil Decay	-0.29	-1.22	-1.34	-0.89	-1.02	-1.06	-1.19	-1.21
Orchard and Vineyard Trimming	ALT_3 Slash Pile Burn	-0.81	-1.85	-1.99	-1.49	-1.63	-1.68	-1.82	-1.84
	ALT_4 Chip and Spread	-0.33	-1.37	-1.51	-1.01	-1.15	-1.20	-1.34	-1.36
		Net emissions after 100 years, tonnes CO2e / tonne Biochar							
Wheat Straw	ALT_1 Natural Biomass Decay	-3.14	-7.14	-7.67	-5.14	-5.63	-5.80	-6.29	-6.31
	ALT_2 Compost then Soil Decay	-1.28	-5.29	-5.82	-3.48	-3.97	-4.14	-4.63	-4.66
Orchard and Vineyard Trimming	ALT_3 Slash Pile Burn	-3.34	-6.52	-7.01	-5.39	-5.90	-6.09	-6.60	-7.04
	ALT_4 Chip and Spread	-1.36	-4.83	-5.32	-3.65	-4.16	-4.35	-4.86	-5.20
Wheat Straw	Biochar C efficiency (g BC C / g BM	0.352	0.354	0.354	0.396	0.396	0.396	0.396	0.398
	Biochar C content (g C / g BC)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
	Biomass C content (g C / g BM)	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Orchard and Vineyard Trimming	Biochar C efficiency (g BC C / g BM	0.40	0.434	0.434	0.45	0.45	0.45	0.45	0.453
	Biochar C content (g C / g BC)	0.81	0.75	0.75	0.80	0.80	0.80	0.80	0.85
	Biomass C content (g C / g BM)	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49

Appendix B: Supporting Data for Carbon Credit Economics Calculations

Overview of the procedure for calculating economics of biochar production for eight biochar production scenarios (four biochar production methods using two feedstocks) as affected by all combinations of

1) feedstock pricing (full price, free, subsidized by tipping fee),
2) carbon credits determined by a baseline approach currently used in the carbon market or by two LCA approaches involving different alternative biomass pathways for each type of biomass (four alternative pathways in total), and
3) additional carbon credits determined by LCA for incorporation of an "in-network" post-production biochar co-composting operation at two levels of compost GHG emission reductions (average and maximum).

Step 1: Baseline calculations of economics for the 8 production scenarios (2 feedstocks, 4 methods) were determined using the spreadsheet shown in Tables 12 and 13 assuming either 1) full price for biomass (+$40/t), free biomass ($0/t), or receipt of a tipping fee (-$40/t) for the biomass. These scenarios were set by changing the biomass costs in the Variable Inputs portion of the spreadsheet shown in Table 10. Costs per tonne CO2e for each scenario were then recorded in Table 14. The baseline carbon credits generated were those that would be assumed by a typical carbon credit registry (e.g., Verra) for biochar for a 100-year period.

Step 2: To calculate economics for these 3 biomass pricing scenarios assuming an LCA of the biochar benefit relative to the 2 alternative biomass scenarios, estimates of total carbon credits for each LCA scenario were substituted for the baseline values. The estimation process involved determining the ratio of the LCA-derived emissions per unit of biomass to those for the baseline (i.e., the simple process used to award carbon credits) emissions per unit of biomass. These ratios are listed in Table B-1 and assume a single emission pulse followed out to 100 years. The baseline carbon credit values were then multiplied by this ratio to arrive at the estimates for the LCA carbon credit values, which are listed in Table B-2. After substituting the LCA carbon credit values for the baseline values in the spreadsheet the costs per carbon credit for each scenario were recorded in Table 14. Costs for a total of 48 combinations were calculated for the three scenario classes of interest: 3 pricing scenarios (as set in the Variable Inputs), 2 alternative biomass scenarios, and 8 biochar production scenarios.

Step 3. Calculation of the economics of the carbon credits produced by incorporation of an "in-network" post-production biochar co-composting operation (two assumed levels of GHG emission reductions) was slightly more complicated than in the previous two steps as it involved combining carbon credits for biochar production with those for co-composting. First, an estimate of the 100-year baseline emissions (t CO2e/t biomass carbon) for the two co-composting scenarios relative to the alternative (composting without biochar) were determined by an LCA calculation parameters for which are described in Section 5.2.2 and Table 15. Values for a single-year pulse were converted to tonnes CO2e / tonne *composted* biomass by multiplying by the biomass carbon contents (assumed to be 0.503 in all instances because composting literature does not distinguish between the woody biomass and straw with respect to GHG emissions). These post-production LCA values, which are agnostic with respect to biochar type or production history, were then scaled in terms of the biomass used to produce biochar, assuming 9 tonnes of compost biomass per tonne of biochar (10% biochar/90% compost for the co-composting process). A key factor in this estimate was the production efficiency (units of biochar produced per unit of biomass) for each of the biochar production methods. Finally, the LCA-derived biochar production emissions were combined with those for the post-production co-composting emissions to calculate an LCA/baseline emissions ratio. As in Step 2, this ratio was then used to estimate the total CO2e emissions for each combination of co-composting GHG emissions reduction, alternative biomass scenario, and biochar production scenario.

The production costs of carbon credits for a total of 144 combinations were calculated using the spreadsheet in Tables 12 and 13 for the four scenario classes of interest: 2 composting GHG-emission reduction scenarios, 3 pricing scenarios (as set in the Variable Inputs), 3 carbon credit scenarios (1 baseline + 2 alternative biomass LCA scenarios (as set by pasting the values for the appropriate LCA results in Row 39), and 8 biochar production scenarios. The results of these calculations were then recorded in Table 14.

Table B- 1. Ratios of the 100-year LCA-derived and baseline carbon-credit values estimated for 4 biochar production methods with 2 feedstocks and assuming economic scenarios for various combinations of biomass cost subsidies, carbon-credit calculations by LCAs with 2 alternative biomass scenarios for each feedstock or baseline approaches, and the incorporation of a post-production biochar co-composting operation at two levels of greenhouse gas reductions. These ratios were used to derive the total carbon credit values in Table B-2.

Maximum Economic Efficiency	Wheat-Straw Feedstock				Orchard and Vineyard Trimmings Feedstock			
Economic Scenario	Manual-Feed Flame Cap Kiln	Automated Continuous-Feed Gasifier	Continuous-Feed Pyrolytic Gasifier	Temperature Slow-Pyrolysis Kiln	Manual-Feed Flame Cap Kiln	Automated Continuous-Feed Gasifier	Continuous-Feed Pyrolytic Gasifier	Temperature Slow-Pyrolysis Kiln
	---------- LCA / Baseline Ratio for 100-yr, t CO2e / t biomass ----------				---------- LCA / Baseline Ratio for 100-yr, t CO2e / t biomass ----------			
Baseline	--	--	--	--	--	--	--	--
S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	--	--	--	--	--	--	--	--
S_1b: Tipping Fee ($40/t)	--	--	--	--	--	--	--	--
S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	-2.640	-1.319	-1.593	-1.370	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-4.664	-1.704	-2.153	-1.758	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-3.196	-1.819	-2.176	-1.913
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-1.550	-1.198	-1.343	-1.254
S_2 + S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	-2.640	-1.319	-1.593	-1.370	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-4.664	-1.704	-2.153	-1.758	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-3.196	-1.819	-2.176	-1.913
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-1.550	-1.198	-1.343	-1.254
S_2 + S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	-2.640	-1.319	-1.593	-1.370	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-4.664	-1.704	-2.153	-1.758	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-3.196	-1.819	-2.176	-1.913
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-1.550	-1.198	-1.343	-1.254
S_3: "In-Network" Co-composting Operation								
S_3a: Average Aerobic Co-Compost Emission Decrease	-0.765	-0.147	-0.238	-0.166	-0.317	-0.140	-0.183	-0.137
S_3b: Maximum Aerobic Co-Compost Emission Decrease	-3.276	-0.628	-1.019	-0.711	-1.359	-0.600	-0.783	-0.587
S_3a + S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	-0.765	-0.147	-0.238	-0.166	-0.317	-0.140	-0.183	-0.137
S_1b: Tipping Fee ($40/t)	-0.765	-0.147	-0.238	-0.166	-0.317	-0.140	-0.183	-0.137
S_3a + S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	-3.405	-1.465	-1.831	-1.536	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-5.429	-1.851	-2.391	-1.924	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-3.513	-1.959	-2.359	-2.050
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-1.867	-1.338	-1.526	-1.391
S_3a + S_1 + S_2: Carbon Credits based on LCA								
S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	-3.405	-1.465	-1.831	-1.536	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-5.429	-1.851	-2.391	-1.924	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-3.513	-1.959	-2.359	-2.050
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-1.867	-1.338	-1.526	-1.391
S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	-3.405	-1.465	-1.831	-1.536	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-5.429	-1.851	-2.391	-1.924	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-3.513	-1.959	-2.359	-2.050
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-1.867	-1.338	-1.526	-1.391
S_3b + S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	-3.276	-0.628	-1.019	-0.711	-1.359	-0.600	-0.783	-0.587
S_1b: Tipping Fee ($40/t)	-3.276	-0.628	-1.019	-0.711	-1.359	-0.600	-0.783	-0.587
S_3b + S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	-5.916	-1.947	-2.612	-2.081	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-7.941	-2.332	-3.171	-2.469	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-4.555	-2.420	-2.960	-2.499
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-2.909	-1.799	-2.126	-1.841
S_3b + S_1 + S_2: Carbon Credits based on LCA								
S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	-5.916	-1.947	-2.612	-2.081	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-7.941	-2.332	-3.171	-2.469	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-4.555	-2.420	-2.960	-2.499
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-2.909	-1.799	-2.126	-1.841
S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	-5.916	-1.947	-2.612	-2.081	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	-7.941	-2.332	-3.171	-2.469	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	-4.555	-2.420	-2.960	-2.499
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	-2.909	-1.799	-2.126	-1.841

Table B- 2. Total carbon credit values used in estimates of 100-year carbon credit costs for 4 biochar production methods with 2 feedstocks and assuming economic scenarios for various combinations of biomass cost subsidies, carbon-credit calculations by LCAs with 2 alternative biomass scenarios for each feedstock or baseline approaches, and the incorporation of a post-production biochar co-composting operation at two levels of greenhouse gas reductions.

Maximum Economic Efficiency	Wheat-Straw Feedstock				Orchard and Vineyard Trimmings Feedstock			
Economic Scenario	Manual-Feed Flame Cap Kiln	Automated Continuous-Feed Gasifier	Continuous-Feed Pyrolytic Gasifier	Temperature Slow-Pyrolysis Kiln	Manual-Feed Flame Cap Kiln	Automated Continuous-Feed Gasifier	Continuous-Feed Pyrolytic Gasifier	Temperature Slow-Pyrolysis Kiln
	-------------------- Total C Credits, t CO2e --------------------				-------------------- Total C Credits, t CO2e --------------------			
Baseline	82	834	3193	6511	236	1211	5014	8974
S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	82	834	3193	6511	236	1211	5014	8974
S_1b: Tipping Fee ($40/t)	82	834	3193	6511	236	1211	5014	8974
S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	216	1100	5087	8920	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	382	1421	6874	11447	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	754	2203	10913	17164
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	366	1451	6734	11254
S_2 + S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	216	1100	5087	8920	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	382	1421	6874	11447	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	754	2203	10913	17164
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	366	1451	6734	11254
S_2 + S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	216	1100	5087	8920	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	382	1421	6874	11447	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	754	2203	10913	17164
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	366	1451	6734	11254
S_3: "In-Network" Co-composting Operation								
S_3a: Average Aerobic Co-Compost Emission Decrease	145	956	3952	7592	311	1381	5931	10203
S_3b: Maximum Aerobic Co-Compost Emission Decrease	351	1358	6445	11141	556	1939	8942	14237
S_3a + S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	145	956	3952	7592	311	1381	5931	10203
S_1b: Tipping Fee ($40/t)	145	956	3952	7592	311	1381	5931	10203
S_3a + S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	279	1222	5846	10001	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	445	1544	7633	12528	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	828	2373	11830	18393
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	440	1621	7652	12483
S_3a + S_1 + S_2: Carbon Credits based on LCA								
S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	279	1222	5846	10001	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	445	1544	7633	12528	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	828	2373	11830	18393
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	440	1621	7652	12483
S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	279	1222	5846	10001	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	445	1544	7633	12528	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	828	2373	11830	18393
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	440	1621	7652	12483
S_3b + S_1: Subsidize Biomass Costs								
S_1a: Free Biomass	351	1358	6445	11141	556	1939	8942	14237
S_1b: Tipping Fee ($40/t)	351	1358	6445	11141	556	1939	8942	14237
S_3b + S_2: Carbon Credits based on LCA								
S_2a: Biomass ALT_1 Natural Decay	485	1624	8339	13550	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	651	1945	10126	16077	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	1074	2931	14841	22427
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	686	2179	10662	16518
S_3b + S_1 + S_2: Carbon Credits based on LCA								
S_1a: Free Biomass								
S_2a: Biomass ALT_1 Natural Decay	485	1624	8339	13550	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	651	1945	10126	16077	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	1074	2931	14841	22427
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	686	2179	10662	16518
S_1b: Tipping Fee ($40/t)								
S_2a: Biomass ALT_1 Natural Decay	485	1624	8339	13550	--	--	--	--
S_2b: Biomass ALT_2 Compost then Soil Decay	651	1945	10126	16077	--	--	--	--
S_2c: Biomass ALT_3 Slash Pile Burn	--	--	--	--	1074	2931	14841	22427
S_2d: Biomass ALT_4 Chip and Spread	--	--	--	--	686	2179	10662	16518