LIFE CYCLE ASSESSMENT OF BIOCHAR FROM POST-HARVEST FOREST RESIDUES

Waste to Wisdom: Subtask 4.7

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EXECUTIVE SUMMARY

This report covers the life cycle assessment (LCA) of the biochar conversion technologies examined as part of *Waste to Wisdom: Utilizing forest residues for the production of bioenergy and bioproducts*. This initiative is investigating the technical and economic feasibility of mobile platforms to process forest residues that would otherwise become waste into bio-based products including pellet fuels, fuel briquettes, and biochar. Systems that produce biochar have the unique potential to provide a valuable soil amendment that can be used on site in the forest to enhance forest soils or remediate areas degraded by compaction, erosion or pollution. Biochar fits nicely into the concept of a circular economy as its production can bring benefits back to the land base.

The scope of this study was to develop a cradle-to-gate life cycle assessment for biochar processing including a life cycle impact assessment (LCIA) to evaluate the environmental footprints from harvest to the thermochemical conversion of biomass into biochar (product manufacturing). Sensitivity analysis was performed on seven input feedstocks with different contaminants and comminution methods based on mass of biochar production. Carbon footprint as well as other environmental indicators were reported for biochar production over the range of feedstocks and over several alternatives scenarios for biomass transportation and alternatives for providing electrical power to the systems.

The primary biochar system under analysis is a mobile pyrolyzer manufactured by Biochar Solutions Incorporated (BSI). The system includes a downdraft gasifier with a blower and other electrical loads that use electrical power generated by either a diesel generator or the Power Pallet, a separate downdraft gasifier, that is coupled to a generator. The BSI system was tested by the Schatz Energy Research Center and performance data were collected and analyzed. In addition, LCA models were developed for two other biochar production systems for comparison, the Oregon Kiln and the Air Burner operating in pyrolysis mode.

Biochar as a bio-based product offers some unique aspects for contributing to the circular economy that LCA is meant to support. To understand how our analysis could be used as part of broader efforts, we also conducted a literature review of previous work on biochar system applications in forestry and biochar LCA in general. The most consistent major contribution to climate mitigation arises from carbon storage in the biochar, and that the categories of avoided emissions from fossil energy, soil, or alternative biomass waste disposal methods were highly variable and dependent on specific scenarios. Biochar produced at higher temperatures is more condensed and less degradable by soil microbial processes, so that it will sequester carbon from the atmosphere for a longer period of time. This condensed carbon is commonly called “fixed carbon.”

The system boundary for the LCA of biochar begins with harvesting of the biomass and ends with finished biochar. The production flow can differ slightly depending on the biochar production system used, feedstock used, location of Biomass Conversion Technology (BCT) site, and fuel used to power electrical loads.

The handling and comminution of the forest residues increase carbon emissions. Systems that can process bulk feedstock such as the Oregon Kiln and Air Burner offer alternatives to forest waste disposal with less feedstock handling input. These systems have few components and are more mobile as compared to the BSI machine, so they can be moved more often to different remote processing sites, reducing the need to haul material within the remote watershed unit. The Oregon Kiln system in particular, offers a viable alternative for sites where feedstocks are thinly and widely scattered and greater mobility is required to bring biochar conversion platforms closer to feedstocks.

Transportation of biomass feedstock is a major source of emissions and the reason for examining these remote operations in the first place. However, there could be an advantage in locating the operation in town where grid power is available. For the BSI system, using a portable biomass gasifier for power generation had lower carbon emissions over a portable diesel generator both at the remote BCT and in town. Grid electricity provided no carbon benefits over the biomass gasifier, but did lower carbon emissions over the diesel generator. Using grid electricity to operate the BSI machine produced a 53 percent decrease in GWP from the diesel generator used at a remote BCT site, but had an 88 percent increase over a remote BCT with Power Pallet. If the biomass gasifier is used to provide electricity for the unit, then there is little advantage in moving the operation to town. For the remote location and 2-hour transportation distance to a town BCT site, all scenarios except biochar produced from medium chips and fueled by diesel had net negative CO2 eq. emission. Once you transport the ground residue and pulpwood 4 hours and use diesel fuel for energy, the net GWP is positive, meaning more carbon is emitted from collection, production, and transport than is stored in the biochar

Feedstock variability has a large impact on both biochar quality and biochar production efficiency. Moisture, contamination and ash content all reduce both quality and efficiency. There is general trend that system GWP decreases as the percent of fixed carbon in the biochar increases. Temperature of operation in all of the biochar systems has an impact on biochar quality. Higher temperature operations produce biochar with greater fixed carbon content resulting in greater reductions in GWP. The higher temperature operation of the Air Burner will always produce a higher quality biochar with more fixed carbon than the other alternatives. For the BSI system, an average fixed carbon in the biochar was 69 percent over all of the feedstocks. Analysis of biochar from the Oregon Kiln and the Air Burner showed fixed carbon contents of 76 and 89 percent, respectively.

A final alternative analysis was to compare the biochar systems to conventional slash pile burning based on emissions. The analysis shows that despite the many challenges of producing biochar in remote locations, there are complementary benefits in providing long term storage of recalcitrant carbon. If efforts are conducted on a significant scale, then the opportunity exists to generate real benefits from reducing fire risk by utilizing large amounts of waste wood. The avoided emissions are directly relevant to human health effects as well as impacting wildfire behavior. All biochar production systems had a net negative carbon emission, while the slash and burn scenarios were nearly carbon neutral (-0.04 mt CO_2 eq.) When the diesel generator is used in the BSI system, there is a 66 percent decrease in NET carbon storage for the tops/pulpwood biochar system and 14 percent decrease in biochar system that used chipped pulpwood.

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GLOSSARY OF TERMS

Autothermal Process - A thermochemical reaction that creates synthesis gas from organic materials using only the heat produced by the reaction itself.

Biochar - A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment that is suitable for use in soils.

Biochar Physicochemical Properties - Those physical and chemical properties of biochar that affect the uses of biochar in soils and the environment.

Biochar quality - Biochar quality is assessed according to the purpose of the biochar use. In the case of biochar used for carbon sequestration in soil, biochar quality is determined by the recalcitrance of the carbon in biochar.

Carbonization - The conversion of an organic substance into carbon or a carbon-containing residue through pyrolysis.

Charcoal - A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment that is suitable for use as a fuel.

Fixed Carbon - Fixed carbon is another term for recalcitrant carbon.

Flame Cap Kiln - A flame cap kiln is a carbonizer that uses a cap of flame both to transfer heat to the feedstock and to prevent oxidation of the finished biochar.

Forest Residues - Woody material not harvested or removed from logging sites in commercial operations as well as material resulting from forest management operations such as pre-commercial thinning and removal of dead and dying trees.

Greenhouse gas (GHG) - Any of the gases whose absorption of solar radiation is responsible for the greenhouse effect, including carbon dioxide, methane, ozone, and the fluorocarbons.

Global warming potential (GWP) - Greenhouse emissions factored to represent CO2 equivalents.

Life cycle assessment (LCA) - Method for the environmental assessment of products covering their lifecycle from raw material extraction to waste treatment.

Life cycle inventory (LCI) - LCA study that goes as far as an inventory analysis, but does not include impact assessment.

Life cycle impact assessment (LCIA) - Phase of an LCA study during which the environmental impacts of the product are assessed and evaluated.

Pyrolysis - The thermochemical decomposition of organic material in an oxygen-limited environment.

Recalcitrant Carbon - In soils, the recalcitrant carbon pool is that fraction of soil organic matter that is resistant to microbial decomposition.

Sequestered Carbon – In the context of biochar, sequestered carbon is the recalcitrant carbon content of biochar that is added to soil.

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1 BACKGROUND OF STUDY

The Biomass Research and Development Initiative (BRDI), established by Congress in 2000, is a joint initiative undertaken by the USDA's National Institute of Food and Agriculture and the U.S. Department of Energy to support the development of bioenergy feedstocks, biofuels and bio-based products. In 2014, the DOE awarded a $5.88 million grant to Humboldt State University, along with 15 regional partners, for a project called *Waste to Wisdom: Utilizing forest residues for the production of bioenergy and bioproducts*. This initiative is investigating the technical and economic feasibility of mobile platforms to process forest residues that would otherwise become waste into bio-based products including pellet fuels, fuel briquettes, and biochar for soil improvement. The other research partners are the University of Washington, Oregon State University, the Bureau of Land Management, USDA Forest Service, USFS Rocky Mountain Research Station, USFS Forest Products Lab, Redwood Forest Foundation, Forest Concepts LLC, Steve Morris Logging, Green Diamond Resource Company, Peterson Pacific Corp., Biochar Solutions Inc., Pellet Fuels Institute and the Forest Business Network LLC.

Feedstock logistics are a key part of the manufacturing process and are one of the primary focus points for the investigation along with analysis of the mobile conversion technologies. The investigation includes both economic and life cycle analysis of the systems. An additional motivation for the work is the benefit to the forest from residue removal and conversion, which can reduce fire risk and support forest restoration and resilience. Systems that produce the biochar product have the unique potential to provide a valuable soil amendment that can be used on site in the forest to enhance forest soils or remediate areas degraded by compaction, erosion or pollution. Biochar fits nicely into the concept of a circular economy as its production can bring benefits back to the land base. This report covers the life cycle assessment (LCA) of the biochar conversion technologies examined as part of the research.

Biochar as defined by the International Biochar Initiative is "A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment." Biochar can be described as a charcoal-like substance that contains a 50 percent or higher content of recalcitrant carbon by dry mass. The scope of this study was to develop a cradle to gate life cycle assessment for biochar processing including a life cycle impact assessment (LCIA) to evaluate the environmental footprints from harvest to the thermochemical conversion of biomass into biochar (product manufacturing). Sensitivity analysis was performed on seven input feedstocks with different contaminants and comminution methods based on mass of biochar production. Carbon footprint as well as other environmental indicators were reported for biochar production over the range of feedstocks. In addition, LCA models were developed for other biochar production systems for comparisons of biochar production techniques when resources and energy inputs vary.

2 INTRODUCTION AND LITERATURE REVIEW

The most extensive forest management challenges in western forests today revolve around fire and watersheds. Large-scale logging and fire suppression have resulted in overstocked stands of small diameter trees that are vulnerable to extreme fire (Noss et al. 2006). As a result of climate change, rainfall and mountain snowpacks have shown a decline, while the summer drought period tends to be longer, increasing fire risk and lowering forest and soil resilience. Active management to remove excess biomass is being prescribed for the Wildland Urban Interface (WUI) and other areas where it is warranted for improved wildfire management, such as overstocked, dense plantations and the creation of shaded fuel breaks. The acreage of forestland that could be treated is extensive and disposal of the waste wood (tops, limbs, and un-merchantable pulpwood) can be expensive. Forest residues generated during commercial logging operations also present a fire risk that must be treated or removed. However, these residues are potentially available for bioenergy and bio-based products, including biochar.

The Waste to Wisdom research project was initiated in order to identify technologies and processes that could utilize these residues for economically valuable bio-based products that could help offset the costs of forest restoration and fuel reduction treatments and provide employment opportunities in rural areas. Because of the high cost of transporting low value forest residues to industrial facilities, the emphasis of this project is on mobile platforms that can perform conversion and manufacturing operations close to where they are generated. Life cycle assessment is a powerful tool for comparing bottom line impacts of the life cycle of a product or process on the environment.

This report presents results from the LCA of a mobile pyrolyzer manufactured by Biochar Solutions Incorporated (BSI). The BSI pyrolyzer was tested extensively by the Schatz Energy Research Center and performance data were collected and analyzed. To provide additional context, we also examined two alternative mobile platform scenarios under development, the Oregon Kiln and the Air Burner, using less extensive, preliminary data sets. Biochar as a bio-based product offers some unique aspects for contributing to the circular economy that LCA is meant to support. To understand how our analysis could be used as part of broader efforts, we also conducted a literature review of previous work on biochar system applications in forestry and biochar LCA in general.

2.1 Biochar and Forests

In recent years, the US Forest Service has evaluated the potential to reduce the cost of restoration treatments and biochar production through mobile, in-woods pyrolysis systems, obtaining biochar as a co-product of mobile bio-oil production systems using forest residues. Since the production facility is located in the woods, there are limited transportation costs for returning the biochar to the forest. Revenues from the energy production could pay for the biochar co-product and for applying it to forest soils (Page-Dumroese et al. 2009).

However, the challenges of implementing mobile plants that produce both bio-oil and biochar are significant and include both technical and economic challenges. Capital and operating costs may exceed the cost of forest residue transportation (Sorenson 2010), yet without transportation subsidies, use of residues in large, stationary facilities may only be feasible where hauling distances are short. More favorable economic conditions for biomass energy production with a biochar co-product could include both higher energy prices and a tax or other mechanism to put a price on carbon emissions that would pay for carbon sequestration (and soil improvement) in the form of biochar. Improvements in technology are also a factor, as new methods being developed by the Waste to Wisdom project could change how forests are harvested and residues are treated, and help make future efforts at in-woods processing more cost-effective.

Other than chipping for biomass energy, the main alternative for biomass disposal is the current practice of incinerating it in onsite burn piles, which can alter soil productivity, increase CO_2 emissions, and produce particulates (Page-Dumroese et al. 2010). Slash pile burning may alter soil microbial populations, destroy seeds, and result in bare soil, which is vulnerable to colonization by invasive species

(Korb et al. 2004). Smoke and particulate production from slash pile burning limits the burning window especially in air-quality limited watersheds, making it more difficult to accomplish the work.

There is concern that large-scale removal of biomass from forests will export nutrients and carbon that is needed to replenish soils. However, not all sites display a noticeable decline in nutrients or carbon after one-time harvest operations (Jang et al. 2015). On sites that are particularly susceptible to nutrient export, climatic changes, or insect and disease stress, biochar could help return nutrients and carbon, and increase water-holding capacity and nutrient cycling capacity of soils as part of forest health restoration strategies (Page-Dumroese, Coleman & Thomas 2015).

Researchers at the US Forest Service have been investigating biochar applications for protecting soil quality, function, and site productivity following biomass removals for fuel load reduction and forest health, and have established both field research sites and pot studies to assess impacts of biochar addition. The US Forest Service is conducting multiple investigations of biochar as tool for improving soil water-holding capacity, reducing bulk density of compacted soils and old roads, restoring range soils and mine sites, filtering sediment to improve water quality, as a seed coating for native plant establishment, and as an amendment in container media for native plant nurseries (Dumroese et al. 2011, Page-Dumroese et al. 2015, Page-Dumroese, Coleman & Thomas 2015, Page-Dumroese et al. 2017, Williams, et al. 2016).

2.2 Unique Features of Biochar

Biochar has sparked great interest amongst researchers and policy makers because of its potential to address some of the toughest global problems, including soil degradation, food security and climate change. Woolf et al. (2010) estimated that the maximum sustainable global technical potential of biochar to reduce emissions of GHG is about 12 percent of the annual anthropogenic net emissions of GHG. Furthermore, they found that, in most cases, conversion of biomass to biochar with energy recovery has a larger potential for climate mitigation than complete combustion of the same biomass as a substitute for fossil fuel energy. The difference in these potentials rests on the carbon intensity of the energy being offset and on the potential of biochar to increase net primary productivity (NPP) of biomass when used as a soil amendment.

Biochar is unique as a forest product because of its potential for multiple environmental benefits accruing not only from its final end use, but also from both avoided emissions during the production process, and from carbon sequestration in soil. However, in order to realize all the promised benefits of biochar, it must be analyzed as a system, not just a product. Only rigorous life cycle analysis can determine if a particular biochar product has resulted in avoided greenhouse gas emissions during its production. The ability of biochar to sequester carbon depends on the physicochemical qualities of the biochar (carbon and ash content, carbon recalcitrance, surface area and other attributes) and on soil environmental conditions.

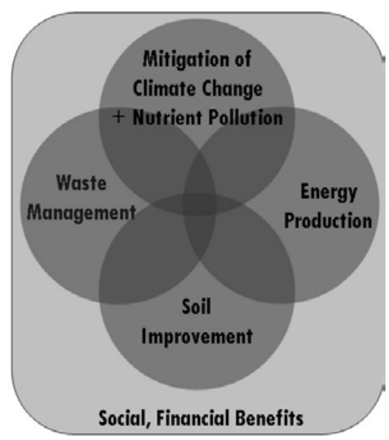

Figure 1 Multiple benefits of biochar. (From Lehman & Joseph, 2009.)

The multiple benefits of biochar can be divided into four, interrelated categories: waste management, energy generation, soil improvement and climate change mitigation (Lehman & Joseph, 2009) (Figure 1). There are many different technologies for producing biochar and many different and widely varying biomass feedstocks that can be used. Hence, there are multitudes of different possible biochar systems. Inevitably, not all biochar systems will be able to achieve all four objectives listed above.

In most cases, biochar systems will show the greatest benefits if waste feedstocks are used. Waste materials that have a disposal cost are usually the most economically viable to use. However, some feedstocks are more challenging to pyrolyze than others. The challenges may come from the physicochemical nature of the feedstocks themselves (for example, wood species and moisture content) or from the difficulty and logistics of collecting and transporting the feedstocks. For instance, wet feedstocks like sewage sludge require drying, and a waste like forest residues is distributed across the landscape and must be collected. Depending on the pyrolysis temperature, pressure, and feedstock moisture content, production of biochar can release heat, combustible gases and condensates. Electricity generation and process heat from pyrolysis are most economically produced in large scale industrial facilities that may be a long distance away from the biomass feedstock sources. Accordingly, many existing biochar production systems do not utilize the energy generated by pyrolysis.

Soil improvement and climate mitigation are the main benefits of biochar. If they did not exist as benefits, there would be little reason to produce biochar. Both are dependent on the final use of biochar, including post-processing and application methods. If the climate impacts of the biochar production process exceed the sequestration value of the biochar when applied to soil, then there will be no net climate mitigation benefit, although there may still be a benefit to soil. Figure 2 gives a schematic view of all the elements of a complete cradle-to-cradle biochar system that can potentially impact atmospheric greenhouse gases (GHG).

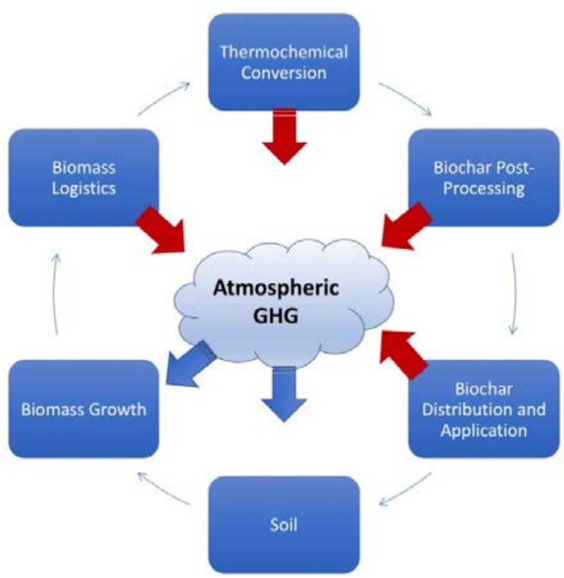

Figure 2 A schematic view of a complete cradle-to-cradle biochar production and use system, showing the elements with greatest potential impact on the carbon cycle and GHG production.

Other potential benefits accruing from the production and use of biochar are also possible, mostly in the realm of avoided emissions. These include: avoided emissions from residue burning or decomposition; avoided emissions by reducing fertilizer inputs; and avoided emissions by substitution of biomass energy generation for fossil fuel energy (Gaunt & Cowie 2009). When biochar is added to soils, it often reduces nitrous oxide emissions from fertilizers (Verhoeven et al. 2016) and it may also result in suppression of CO2 emissions from soil microbial processes, known as "negative priming" (Wang et al. 2016). Many other impacts could also be considered, including direct and indirect land use change and soil albedo, among others (Meyer et al. 2011).

2.3 Biochar Impact Categories

Given uncertainties and the state of current knowledge, producing a complete cradle-to-grave LCA for any biochar system is a large undertaking no matter how tightly one draws the system boundaries. However, we can be confident that under the right circumstances, both yield increases and stable soil carbon can result from the application of biochar in soil (Jeffrey et al. 2015, Jeffery et al. 2017, Novak et al. 2016, Zygourakis 2017). Given all the complexities of a biochar system, what is the best approach for conducting LCA? Previous investigations have taken different approaches, drawing system boundaries in different places or choosing to emphasize different impact categories.

Cowie et al. (2012) in a review of biochar sustainability, concluded that the most consistent major contribution to climate mitigation arises from carbon storage in the biochar, and that the categories of avoided emissions from fossil energy, soil, or alternative biomass waste disposal methods were highly variable and dependent on specific scenarios. They also identified biochar production temperature as the most important indicator of biochar recalcitrance. Biochar produced at higher temperatures is more condensed and less degradable by soil microbial processes, so that it will sequester carbon from the atmosphere for a longer period. This condensed carbon is commonly called "fixed carbon."

2.4 LCA of Biochar

There have been many studies reporting the LCA of biochar production. Most are difficult to compare based on functional unit or based on the scope or system boundaries of the LCA. Regarding the choice of a functional unit for analysis, Hammond et al. (2011) found that carbon abatement per unit of energy delivered is not an appropriate unit for comparing different biochar systems because energy delivered is not the primary product of a biochar system. Additionally, they concluded that while CO_2 eq. per oven dry ton (odt) of biomass feedstock was an appropriate unit for comparing to other bioenergy systems, CO_2eq. per odt of biochar product was best for comparing between biochar systems. Their results found that a starting estimate for the climate mitigation potential of a biochar system was equal to one metric ton of CO_2eq. per oven dry ton of biomass.

Roberts, et al. (2010) chose one metric ton of dry biomass as the functional unit for their biochar-pyrolysis system, which compared corn stover, yard waste, and switchgrass feedstocks used in a bioenergy facility. The reference flows for the system were the mass and C in the biomass feedstock and the energy associated with biochar production. They followed the net energy of the functional unit through the system, incorporating all energy inputs to the system and energy produced by the system.

Energy produced by the system included syngas energy and energy from avoided processes such as fossil fuel production, fertilizer production, and composting. The net climate change impact was calculated as the sum of the net GHG reductions (biochar sequestered carbon and avoided emissions) and the net GHG emissions. Avoided emissions included fossil fuel production and combustion, soil N_2O emissions, fertilizer production, and composting. Biogenic CO_2 emissions were accounted for in the C balance of the biomass to biochar pyrolysis system, but biochar improvements to soil productivity or NPP were not accounted for; however, indirect land use change for the switchgrass feedstock only (caused by changing land use from food to fuel production) was included. The biochar value in their analysis depended on the fertilizer value of inputs of potassium and phosphorus from ash incorporated in the biochar, improved fertilizer use efficiency, and GHG reductions. They assumed that the stable, fixed carbon in biochar is 80 percent of the mass of biochar. If the energy from the system replaced coal-generated electricity they concluded that the biochar system using corn stover feedstock would result in 29 percent emissions reductions over using the biomass for energy only. In this analysis, indirect land use change and agronomic inputs to grow stover or switchgrass had the largest impacts. Transportation of feedstocks to processing facilities had relatively minor impacts. The reverse is more likely the case for forestry feedstocks where agronomic inputs are minimal and transportation distances are longer.

Lee et al. (2011) examined many alternative fates for a unit of biomass in different energy and soil amendment uses. Based on air emissions and soil application impacts, they found that a biochar energy system produced less GHG emissions than composting, combustion for energy or conversion to cellulosic ethanol.

Forest Service researchers (Bergman & Gu 2014, Gu & Bergman 2016) performed a gate-to-gate LCI on an advanced biomass pyrolysis gasifier using wood chips to produce syngas for electricity generation and biochar. Biochar in this case made a significant reduction in the global warming impact of the generated electricity as compared to either coal or natural gas electricity generation. The biochar effect was attributed to carbon sequestration value only, without analyzing further effects of applying biochar in soil. Many other biochar LCA studies have taken a similar approach, essentially looking at the biochar product as a GHG offset to the climate impact of a biomass energy generation platform (Hudiburg et al. 2017, Homagain et al. 2015, Ramachandran et al. 2017).

Various other biochar LCAs have looked beyond the direct carbon sequestration values of biochar to analyze its impact on avoided soil emissions of GHG, reduced fertilizer use, agronomic yield increases and transportation sensitivities for applying biochar closer to where it is produced (Wang et al. 2014, Peters et al. 2015, Munoz et al. 2017, Rosas et al. 2015, Pereiera et al. 2016). Transportation sensitivities are often significant in both the feedstock logistics phase and the biochar distribution and application phase.

In the current LCA of a mobile pyrolysis platform for forestry residue, energy production has already been excluded from the system. Impacts of biochar return to the soil on NPP and the dynamics of soil carbon sequestration have also been excluded from the explicit analysis, however, given that biochar recalcitrance (fixed carbon) is a function of biochar production temperature and feedstock quality, biochar quality has been included as a focus for sensitivity analysis.

3 BIOCHAR MOBILE PLATFORMS IN THIS ANALYSIS

3.1 Description of BSI Machine

The BSI machine (Biochar Solutions, Inc.) is a down-draft gasifier that uses chipped or ground feedstock, loaded into the top of the reactor (Figure 3). A blower draws air and exhaust gas through the reactor to a flare and thermal oxidizer, while char is removed from the bottom of the reactor with an auger, in a continuous process. It is rated to process 0.23 metric ton (mt) per hour (mt/hr) of dry biomass (500 lb/hr) and produce 0.05 mt/hr (100lb/hr) of biochar.

Figure 3 BSI biochar production system. Image credit: Schatz Energy Research Center.

The following information was provided in "Biochar Testing and Results Report" (Schatz Energy Research Center 2016). The operation begins with the biomass feedstock loaded into the hopper (14). Feedstock is manually transferred from the hopper (14) onto the conveyor (15) which transports the feedstock into the reactor (1). The reactor consists of two concentric cylinders with a 6-inch gap between them. Feedstock is loaded into the inner cylinder maintaining a bed depth between 18 and 48 inches. The reactor blower (5) pulls air into the reactor (1) through the dropbox (2), and forces gas through the exit to the flare (3). Feedstock loaded into the top of the reactor is heated by partial combustion as it moves downward through the reactor. As the oxygen levels are depleted near the bottom of the bed, biomass is converted into biochar by gasification. After biochar is formed, the reactor blower pulls it through the gap between inner and outer reactor cylinders and into the dropbox (2). The biochar enters an auger that is cooled by an external water jacket and exits through an airlock (10) which maintains negative pressure in the system while allowing solid biochar to exit and is collected into metal drums (11). The system is equipped with a biomass drying system, but this did not operate effectively for this study.

For more detailed on the production of biochar using the BSI unit please refer to the Biochar Testing and Results Report (SERC 2016).

3.2 Description of Oregon Kiln

The Oregon Kiln consists of a simple metal container known as a flame cap kiln. These kilns work on the principle of flame carbonization, a pyrolysis method that uses a cap or curtain of flame to exclude oxygen from the biomass. These technologies are characterized by low to extremely low capital cost and using bulk woody debris as feedstock with no requirement for chipping and transport of raw biomass. These kilns are operated in batch mode and can have a volumetric production capacity ranging from several cubic feet up to about 20 cubic yards (Wilson 2015, Wilson 2017, Page-Dumroese et al. 2017).

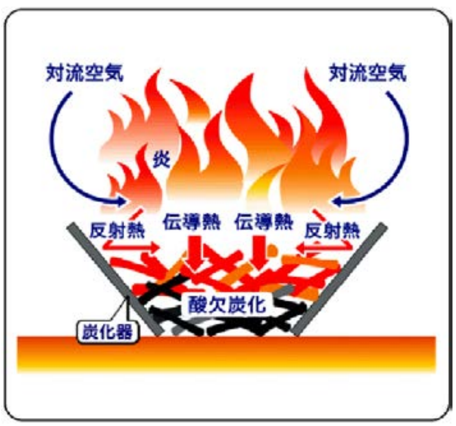

Figure 4 "Smokeless Kiln" sold by the Moki Manufacturing Co., Ltd of Japan. This diagram illustrates the air flows and flame cap that produce the pyrolysis effect.

The Oregon Kiln was inspired by the "Smokeless Kiln" manufactured in Japan by the Moki Co. (Figure 4). This cone-shaped kiln makes high quality, well-carbonized biochar with a reported biomass to char conversion efficiency of 13 to 20 percent, depending on the feedstock used (Inoue et al. 2011). To start the kiln, a fire is kindled in the bottom. Once a layer of glowing coals has formed, new wood is added slowly in layers. Each new layer bursts into flame, excluding air from the layer below and allowing pyrolysis to take place. Because there is always a flame present on top, most of the smoke burns in the flame. When the kiln is full of char, it is quenched by adding water or excluding air with a lid or cap of dirt. The Oregon Kiln is an inverted, truncated pyramid constructed of 14-gauge mild steel, with a solid bottom and a five-foot square top base, a four-foot square bottom base and a height of two feet. Total capacity is 40 cubic feet (1.1 m^3). It is optimized for low cost manufacturing and use in forest settings as an alternative to pile burning (Photo 1).

Photo 1 Oregon Kiln operating in a forest setting. Images credit: Wilson Biochar Associates (wilsonbiochar.com).

3.3 Description of Air Curtain Burners Operating in Pyrolysis Mode

An air curtain burner is a large, refractory-lined box equipped with a powerful blower that is used to incinerate biomass to ash (Photo 2). However, by changing some of the operating parameters, these units can be used to produce biochar. Several manufacturers make these units, but we focused our investigation on the units produced by Air Burners, Inc. The company website explains the principle of operation: "The purpose of the air curtain is to stall or slow down the smoke particles on their way out of the Fire Box. In doing this, the particles are subjected to the highest temperatures in the Fire Box. Stalling the smoke particles in this region just under the air curtain causes them to re-burn, further reducing their size to an acceptable limit" (Figure 5).

Photo 2 Air Burner operating on the Siskiyou National Forest, May 2017. Image credit: Wilson Biochar Associates (wilsonbiochar.com).

The US Forest Service San Dimas Technology and Development Center (SDTDC) investigated Air Curtain Burners and recommended their use for incinerating forest waste with low emissions (Schapiro 2002). An in-depth analysis of air curtain burner emissions came to similar conclusions but also found that in some cases the air curtain burners produced very low particulate emissions even when the blower was turned off (Miller & Lemieux 2007). A conversation with the Matt O'Connor of Air Burners, Inc, confirmed the idea that these units can make biochar when blower rates, feedstock loading rates, or feedstock moisture are varied (personal communication with Kelpie Wilson, July 16, 2015). During a fuel reduction project on the Siskiyou National Forest in May 2016, the contractor who operated the Air Burner was able to fill the box with biochar simply by adjusting the loading rate of the fuel.

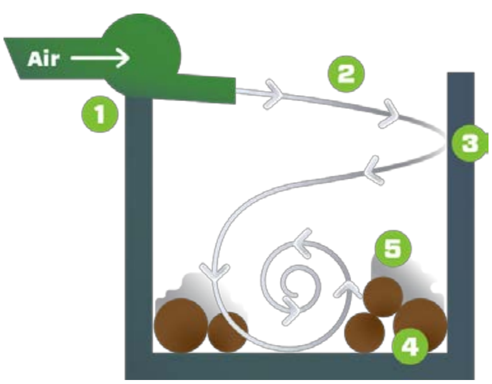

Figure 5 Air Burner principle of operation: 1. Air manifold; 2. Air curtain; 3. Firebox refractory wall; 4. Wood waste or fuel; 5. Smoke and particulates. Image from www.airburners.com

4 METHODOLOGY

4.1 Life Cycle Assessment

Life-cycle assessment (LCA) has evolved as an internationally accepted method to analyze complex impacts and outputs of a product or process and the corresponding effects they might have on the environment. LCA is an objective process to evaluate a product's life cycle by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials uses and releases on the environment; and to evaluate and implement opportunities to effect environmental improvements. LCA studies can evaluate full product life cycles, often referred to as "cradle-to-grave," or incorporate only a portion of the product's life cycle, referred to as "cradle-to-gate," or "gate-to-gate." This study can be categorized as a cradle-to-gate LCA, as it includes forestry operations though the production of biochar.

As defined by the International Organization for Standardization (ISO 2006), LCA is a multiphase process consisting of: 1) Goal and Scope Definition; 2) Life Cycle Inventory (LCI); 3) Life Cycle Impact Assessment (LCIA); and 4) Interpretation (Figure 6). These steps are interconnected and their outcomes are based on goals and purposes of a particular study.

An LCA begins with a project goal, scope, functional unit, system boundaries, any assumptions and study limitations, method of allocation, and the impact categories that will be used. The key component is the LCI, which is an objective, data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases occurring within the system boundaries. It is this information which provides a quantitative basis for comparing wood products, their manufacturing processes, and most importantly from the forest industry point of view, wood products performance against competitors who use other resources to create alternative products.

The LCIA process characterizes and assesses the effects of environmental releases identified in the LCI into impact categories such as global warming, acidification, carcinogenics, respiratory effects,

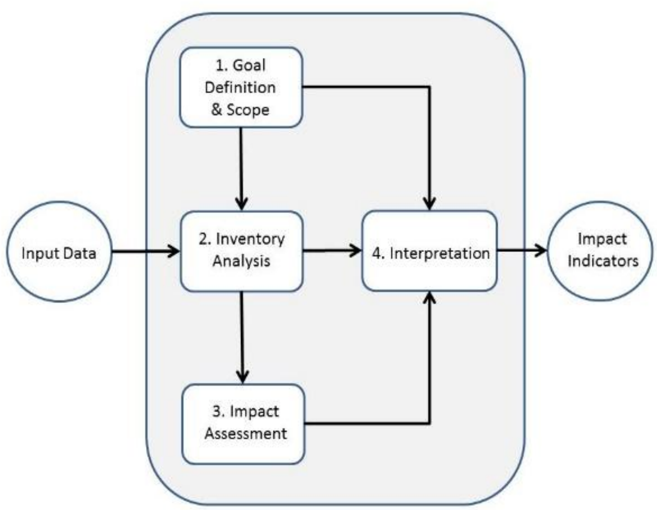

Figure 6 Steps involved in a Life Cycle Assessment

eutrophication, ozone depletion, and smog. For assessing the environmental impacts of biochar production, the TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) impact method was used. TRACI is a midpoint-oriented LCIA methodology developed by the U.S. Environmental Protection Agency specifically for the U.S. using input parameters consistent with U.S. locations (Bare 2011). TRACI is available through the LCA software (http://www.pre-sustainability.com/simapro).

The LCIA establishes the link between the LCI results and potential environmental impacts. These impact indicators provide general, but quantifiable, indications of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 1. Environmental impacts are determined using the TRACI method (Bare 2011).

Table 1 Selected impact indicators, characterization models, and impact categories

Impact Indicator	Characterization Model	Impact Category
Greenhouse gas (GHG) emissions	Calculate total emissions in the reference unit of CO_2 equivalents for CO_2, methane, and nitrous oxide.	Global warming
Releases to air decreasing or thinning of ozone layer	Calculate the total ozone forming chemicals in the stratosphere including CFCs HCFCs, chlorine, and bromine. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total sulfur dioxide equivalent for releases of acid forming chemicals such as sulfur oxides, nitrogen oxides, hydrochloric acid, and ammonia. Acidification value of SO_2 is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication

Each impact indicator is a measure of an aspect of a potential impact. This LCIA does not make value judgments about the impact indicators, meaning comparison indicator values are not valid. Additionally, each impact indicator value is stated in units that are not comparable to others. For the same reasons, indicators should not be combined or added.

The life cycle interpretation is a phase of LCA in which the findings of either the LCI or the LCIA, or both, are evaluated in relation to the defined goal and scope to reach conclusions and recommendations. This final step in a LCA involves an investigation of significant environmental aspects (e.g., energy use, greenhouse gases), their contributions to the indicators under consideration, and which unit processes in the system are generating the emissions. For example, if the results of a LCIA indicate a particularly high value for the global warming potential indicator, the analyst could refer to the inventory to determine which environmental flows are contributing to the high value, and which unit processes contribute to those outputs. This is also used as a form of quality control, and the results can be used to refine the scope definition to focus on the more important unit processes. This step also supports arriving at more certain conclusions and supportable recommendations.

4.2 Biogenic Carbon

It is known that tree growth and fuel combustion result in various fluxes of CO_2. The appropriate methodology for assessing these fluxes is the Global Warming Potential (GWP). Values are factored to kilograms of carbon dioxide equivalents (kg CO_2 eq.)[1]. GWP compares the amount of heat trapped by a certain mass of the gas in question to the amount heat trapped by a similar mass of carbon dioxide. GWP is an indicator that reflects the relative effect of a greenhouse gas in terms of climate change considering a fixed time, commonly 20, 100, or 500 years. For example, the 20-year GWP of methane is 56, which means if the same weights of methane and carbon dioxide were introduced into the atmosphere, methane will trap 56 times more heat than the carbon dioxide over the next 20 years. TRACI uses a 100-year time frame.

Since the beginning of recorded history, wood has provided important benefits to society including products for shelter, raw materials for manufacturing, and fuel for heat. Today's challenge is to effectively use our wood resources without adversely affecting our environment. For example, burning wood as a substitute for fossil fuels is an important part of reducing fossil carbon emissions to the atmosphere that contribute to global warming (Lippke and Puettmann 2013, Puettmann and Lippke 2013, Lippke et al. 2011).

Wood provides both a source of carbon released to the atmosphere and a storehouse for carbon in trees. Growing trees absorb CO_2 from the atmosphere as part of the photosynthesis process. Decaying dead trees and disposal of wood products release much of that carbon back into the atmosphere. Under sustainable forest management, a carbon balance is reached where the carbon released does not exceed the carbon absorbed. This balance supports using sustainably grown wood to reduce the one-way flow of carbon from fossil fuel combustion without diminishing the carbon stored in the forest. In this study, we considered carbon neutrality when comparing different biochar processes but did not consider carbon neutrality when conventional slash burning was compared to biochar production. Results are presented in terms of net carbon emissions for all biochar production systems and slash burning.

[1] To convert from CO_2 to carbon, multiply CO_2 emission by 0.273.

4.3 Goal and Scope

The goal of this work was to determine energy and material inputs and outputs associated with the production of biochar. The original scope of this study was to develop a cradle-to-gate LCA of Biochar Systems Inc (BSI) portable biochar production system and associated upstream processes (e.g. harvesting of biomass and feedstock preparation). Early in the analysis, the scope was expanded to include two additional biochar production systems, the Oregon Kiln and the air curtain burner. The LCA covers the impacts of both the input materials of fuels and electricity, and the outputs, including the marketable biochar, wastes, and emissions. Feedstock collection and comminution were obtained from Oneil et al. (2017); biochar production data for the BSI unit were provided by Schatz Energy Research Center, Humboldt State University (2016); and from Wilson Biochar Associates for the Oregon Kiln and air curtain burner. Data for other fuels and materials were obtained from public databases (NREL 2017)

4.4 Functional Unit

Establishing the functional unit is an important part of an LCA to allow for meaningful comparisons between different materials and alternatives. The functional unit for the biochar LCA is one metric ton of marketable biochar. For comparison between feedstock inputs and biochar systems, the functional unit percent of fixed carbon in the biochar was used to present results. A third functional unit was for comparison with slash pile burning, this unit was 1 metric ton of forest residue (oven dry basis).

4.5 System Boundaries

The system boundary for the LCA of biochar begins with harvesting of the biomass and ends with finished biochar. The production flow can differ slightly depending on the biochar production system used, feedstock used, location of Biomass Conversion Technology (BCT) site, and fuel used for energy (Figures 7, 8, and 9).

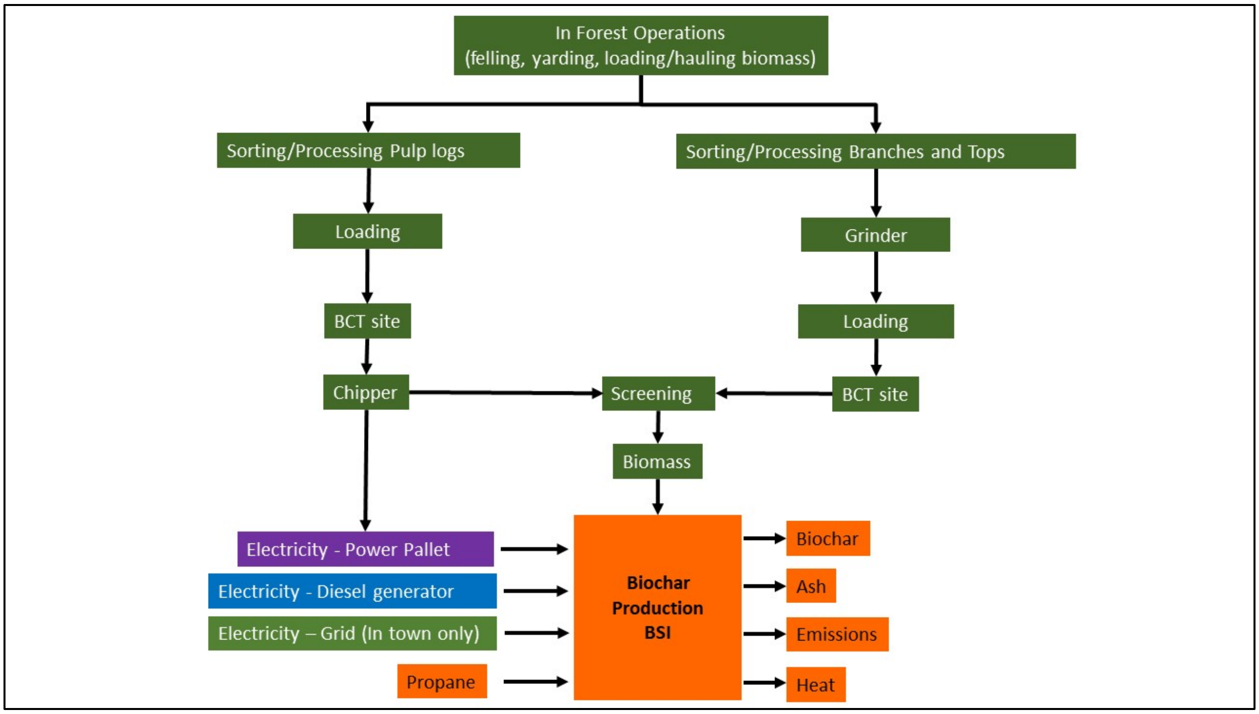

Figure 7 System boundary for production of biochar using the BSI system at either a remote or in town BCT site.

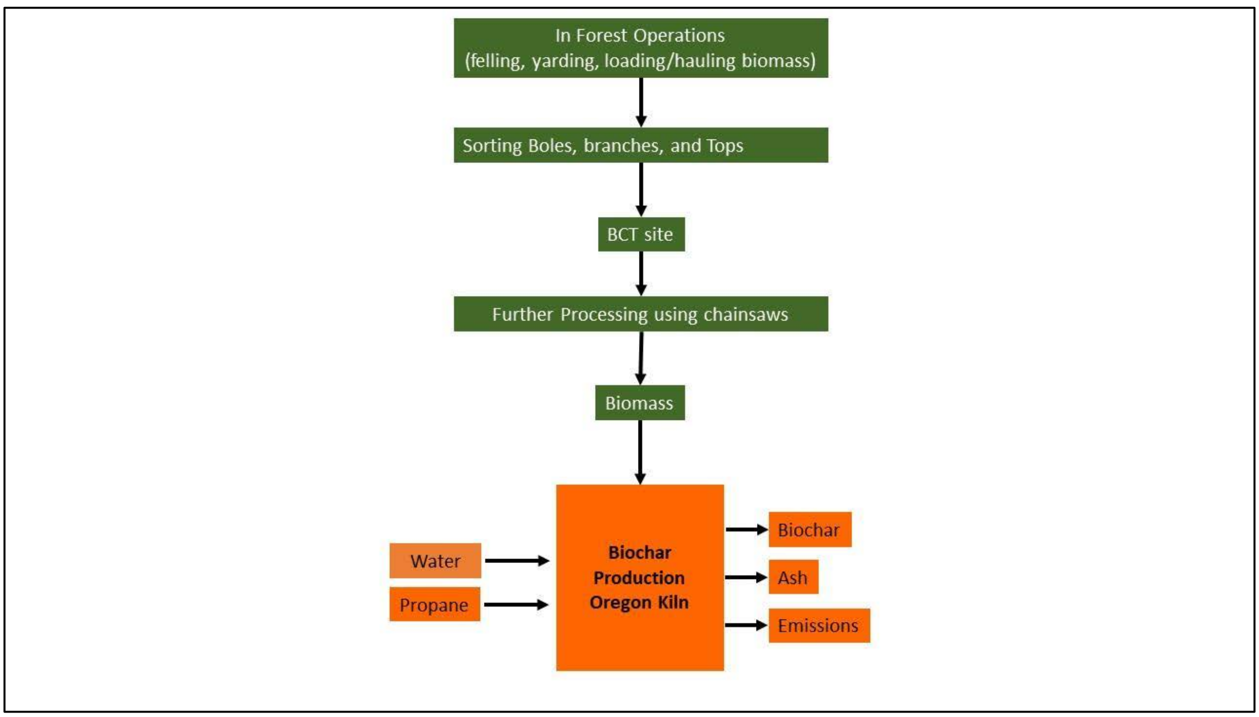

Figure 8 System boundary for production of biochar using the Oregon Kiln

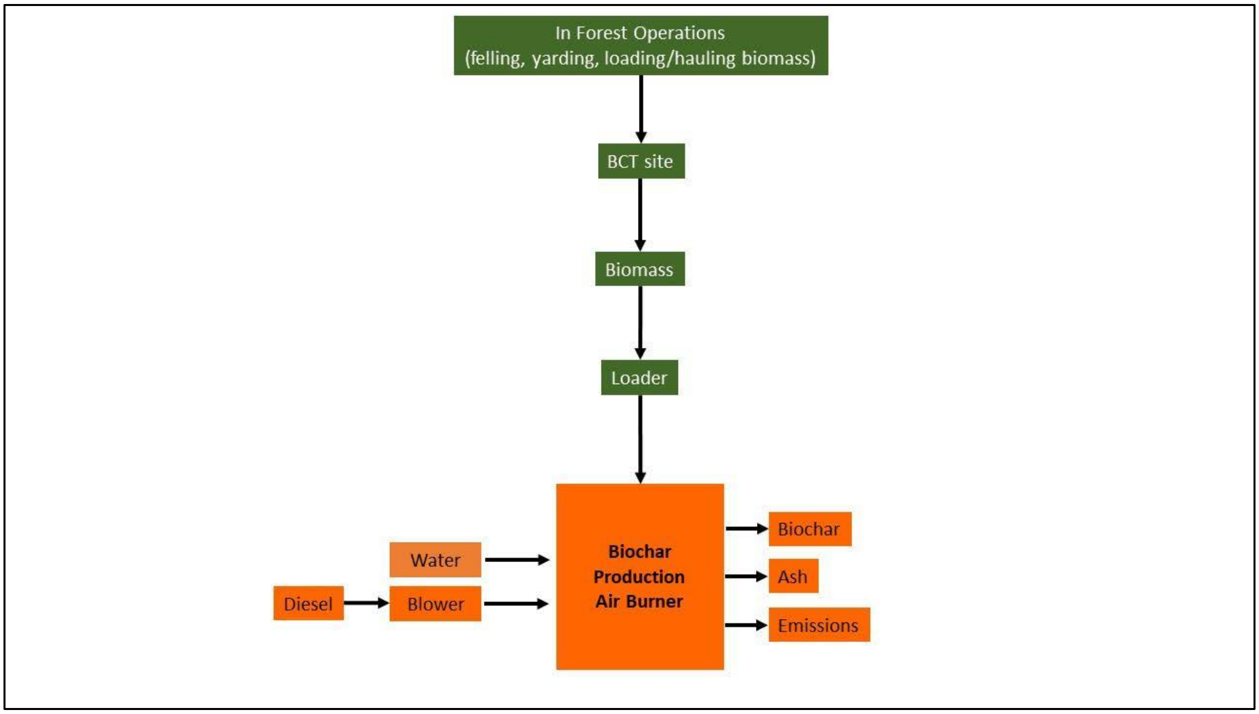

Figure 9 System boundary for production of biochar using the Air Burner.

5 DATA QUALITY AND ASSUMPTIONS

Operations inputs for biochar production including energy consumption, resource inputs, and biochar outputs was collected from actual operations for the Oregon Kiln, Air Burner, and the BSI unit. Where data was lacking assumptions were made based on speaking to experts or published reports.

5.1 Remote BSI Biochar Production

- Emission factors based on Severy et al 2017 (Table 14 in this report)
- All weights of forest residues based on oven dry mass
- All moisture contents based on oven dry basis
- Chipped residues were from clean pulpwood
- Ground residues were generated from tops, 9% soil pulpwood, and clean pulpwood
  Electricity is generated from medium chips from pulpwood fed into a biomass gasifier (Power Pallet)
- Electricity is generated from diesel fuel generator
- Only softwood forest residues were modeled
- LCI inputs based on SERC (2016) (Table14 in this report)
- Conversion efficiencies based on SERC 2016
- All forest residues are considered waste, no inputs associated with forest management or harvesting included
- All drying of residues are assumed to be air dried below a 33 percent (oven dry basis).

5.2 In-town BSI Biochar Production

- Same assumption from 5.1
- Electricity is generated from grid electricity
- Transportation impacts from remote landing to in-town BCT site based on Oneil et al. 2017
- Transportation distances were for 2 and 4 hours from remote landing to BCT site
- All residue preparation machines (chipper, grinder, screener) operated by diesel fuels

5.3 Remote Oregon Kiln Biochar Production

- Emission factors based on Cornelissen et al. 2016
- All weights of forest residues based on oven dry mass
- All moisture contents based on oven dry basis
- Only softwood forest residues were modeled
- Residues collection for tops and pulpwood
- LCI inputs based on Wilson Biochar Associates – estimates from field experience
- Conversion efficiencies based on Cornelissen et al. 2016
- All forest residues are considered waste, no inputs associated with forest management or harvesting included.

5.4 Remote Air Burner Biochar Production

- Emission factors based on Cornelissen et al. 2016
- All weights of forest residues based on oven dry mass
- All moisture contents based on oven dry basis
- Only softwood forest residues were modeled
- Residues collection for tops and pulpwood
- LCI inputs based on Wilson Biochar Associates – estimates from field experience
- Conversion efficiencies based on Cornelissen et al. 2016
- All forest residues are considered waste, no inputs associated with forest management or harvesting included

6 DATA COLLECTION AND THE LCI MODEL

Data for the LCA of biochar was collected from a variety of sources and contained both primary and secondary data (Table 2).

Table 2 Data sources and type used in the LCA of biochar production

Data Type	Data source	Notes
BSI Biochar Machine	SERC	
Air Burner	Wilson Biochar Associates	Estimates from field experience
Oregon Kiln	Wilson Biochar Associates	Estimates from field experience
Residue Collection	Oneil et al 2017	
Biochar emission factors	Severy et al. 2017	
Slash emission factors	Oneil et al 2017	
Propane	LPG, combusted in industrial equipment/RNA	DATASMART Life Cycle Inventory Package
electricity grid	Electricity, at eGrid, NWPP, 2008/RNA U	DATASMART Life Cycle Inventory Package
Diesel fuel	Diesel, combusted in industrial equipment NREL/US U	DATASMART Life Cycle Inventory Package
Gasoline	Gasoline, combusted in equipment NREL/US U	DATASMART Life Cycle Inventory Package

6.1 BSI Biochar Production

Data collection for the BSI biochar system encompasses a cradle-to-gate system boundary (Figure 6). It begins with the collection of the biomass using traditional harvesting mechanisms, transporting the biomass to a landing, processing the biomass, transporting to a BCT site, further processing of biomass if needed, and ending with finished marketable biochar.

6.1.1 *Forest Resources*

All data used for feedstock input into the biochar production system was based on weighted average volume available from five regions: 1) Longview, Washington; 2) Warm Springs, Oregon; 3) Oakridge, Oregon; 4) Lakeview, Oregon; and 5) Quincy, California (Oneil et al. 2017). All sites considered produced >10 oven dry ton (ODT) biomass/acre, and of those sites, only 50 percent of the biomass is technologically accessible due to terrain, turnout limitations, and other biomass recovery limitations. For the remote BCT site (Figure 9), haul time is limited to a maximum of 1 hour from harvest. Haul time is limited to a maximum 2 and 4 hours from the remote BCT site to a possible "in town" BCT site (Longview, Warm Springs, Oakridge, Lakeview, and Quincy) (Figure 10). Hauling operations were separated into two distinct operations – one for pulp quality material (Photo 3) and one for tops and branches. Pulp was hauled to the BCT site (remote or in-town) as whole logs using a mule train. Tops and branches were ground at the landing and hauled to a remote BCT site using a dump truck with a hoist. For the 2- and 4-hour haul distances to an in-town BCT site, a truck + trailer was used for efficient use of the travel time. At each location (remote or in-town) the pulp logs were chipped using a medium chipper or a micro chipper, screened, and loaded into the BSI unit (Figure 6). Tops and branches were ground, screened, and loaded into the BSI unit.

Photo 3 Pulp logs and top/branches at landing in southern Oregon. Photo credit: John Sessions.

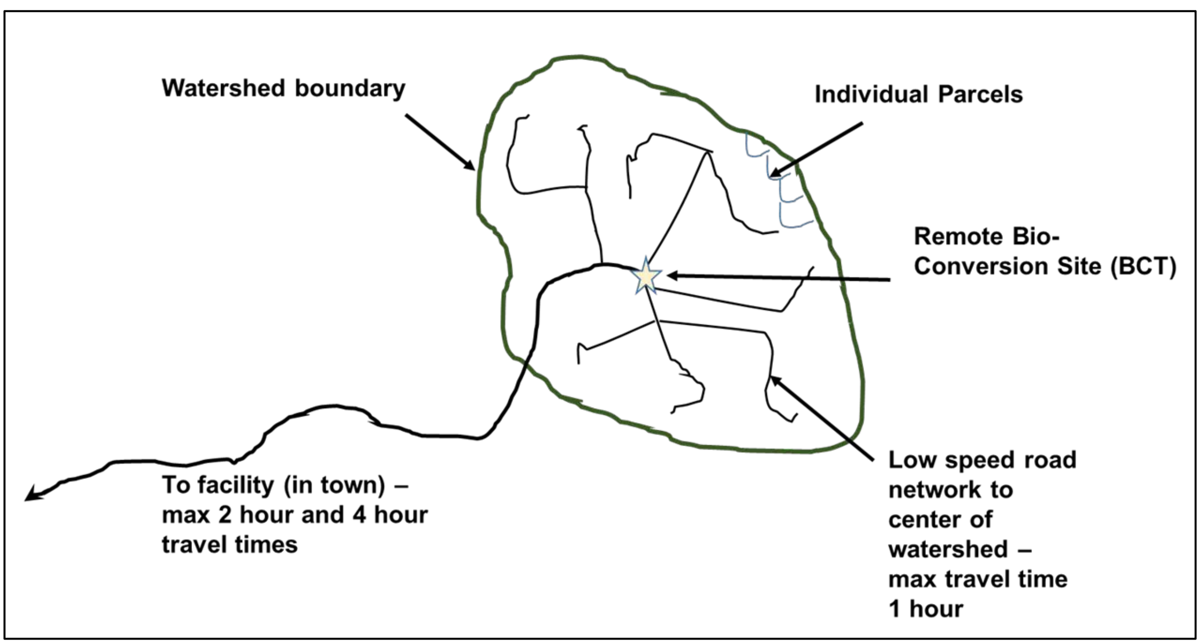

Figure 10 Example of the location of a remote BCT site. There would be several watershed boundaries within a harvest region located near Longview, WA, Warm Springs, OR, Oakridge, OR, Lakeview, OR, and Quincy, CA. The star represents the remote BCT site centrally located. Drawing credit: Oneil et al. 2017

Forest residue collection and processing served as an input into the BSI, Oregon Kiln, and Air Burner biochar production systems. For the BSI system, forest residue processing took place at a 1.) remote biomass conversion technology (BCT) site or 2.) at an in-town location). At the remote site, transportation was limited to a maximum collection area of one mile (Figure 10). The in-town BCT site involved additional transportation of the forest residues with a maximum transportation distance of 2 and 4 hours.

All forest residues were considered waste and therefore forestry operations related to management and harvesting were excluded from this LCA. For more detailed information regarding different harvesting scenarios, transportation, and processing mechanisms including forestry operations, see Oneil et al. (2017). A number of equipment configurations were modeled in the LCA on biomass recovery (Oneil et al. 2017). The equipment that applied to the scenarios for biochar production are reported in Table 3. For a complete understanding of biomass collections systems and machine productivity rates refer to Oneil et al 2017.

Table 3 Woody biomass recovery equipment and fuel consumption used in the LCI model for biochar. Fuel consumptions are based on moving or handling or processing 1 metric ton of forest residue.

Equipment	Manufacturer	Size	Fuel consumption rate	Used for
Loader		250 HP	0.60 L/ton	Feeding grinder or chipper
Loader	John Deere 2954D		0.71 L/ton	Loading pulp logs
Loader	John Deere 2954D		0.35 L/ton	Sorting logs and pulpwood
Large grinder	Peterson Pacific horizontal grinder	1050 HP	2.99 L/ton	Grinding
Large chipper	Mobark chipper	875 HP	0.55 L/ton	Chipping
Microchipper	Peterson Pacific model 4300	765 HP	2.55 L/ton	Chipping
Dump truck			0.65 L/ton	Hauling – in unit, high utilization
Tractor			0.29 L/ton	Hauling – at staging site
Deck screener	Peterson Pacific		1.5939 L/ton	Screening

Table 4 lists the total fuel requirements for residue collection and handling, processing (chipped or ground), loading, and transportation to and from the landing to a designated BCT site. Three locations were modeled for the BCT site: 1. Remote at the landing; 2. Transportation distance of 2 hours; and 3. Transportation distance of 4 hours. The in-town locations are based on existing infrastructure and would have the ability to use grid electricity to operate feedstock preparation (chipper and screener) and the biochar machine.

Table 4 Diesel requirements for cradle-to-landing feedstock preparation for production of one metric ton of biochar (Oneil et al. 2017)

	Unit per ton	Ground clean	Ground, 2/3 bole, 1/3 tops	Ground, 9% soil	Chipped, medium, clean	Chipped, small, clean
Remote, diesel	L	53	50	62	84	60
In-town, 2hr, diesel	L	67	69	78	104	72
In-town, 4hr, diesel	L	91	94	107	138	92

6.1.2 *BSI Biochar Production for the LCA model*

The BSI biochar machine was first tested in August 2014 in Pueblo, Colorado. The focus was on what effects wood species, feedstock moisture content, and feedstock comminution type and quality had on machine operations (SERC 2016). In the end, seven feedstock combinations representing both hardwoods and softwoods, chipped or ground, and different levels of contaminations were tested in the BSI machine (Table 5).

Table 5 Feedstock quality and comminution type tested in the BSI machine

Species	Contaminant	Comminution method	Ash content	Moisture content (wet basis)	Moisture content (dry basis)
Conifer	None	Ground	1.68%	16.93%	20.39%
Conifer	2/3 bole, 1/3 tops	Ground	3.65%	16.20%	19.33%
Conifer	9% soil	Ground	11.45%	14.91%	17.53%
Conifer	none	Chip, medium	0.28%	31.14%	45.23%
Conifer	none	Chip, small	2.13%	20.66%	26.04%
Hardwood	none	Ground	0.60%	15.48%	18.31%
Pinyon & Juniper	As received	Ground	21.39%	9.71%	10.75%

According to the Schatz Energy Research Center report (2016), the biochar machine successfully processed all feedstock types (Table 5 but operation became more difficult and the quality of the biochar decreased when the ash content of the feedstock was greater than 15 percent or the moisture content of the feedstock was above 25 percent on a wet basis. Biochar quality is based on the percent fixed carbon. Both ash and moisture were found to decrease the percent or yield of fixed carbon in the biochar (SERC 2016). When there are higher levels of ash and moisture in the feedstock, more fixed carbon is consumed during gasification in the reactor, which results in less fixed carbon content in the biochar (SERC 2016). Higher amounts of fixed carbon in the biochar give both a higher value energy product and a soil amendment with greater carbon sequestration potential. Following these guidelines, the LCI model limited the analysis to those feedstocks that contained less than 15 percent ash content and lower than 25 percent moisture content (33%, dry basis) (Table 6).

Duplicate tests were performed for each of the seven combinations listed in Table 6. Medium chips are produced from pulpwood and represent a very likely source for biomass feedstock used in biochar production systems. Of the two test runs for the medium chip feedstock, moisture contents were 37 and 25 percent. The average moisture content for the medium chip was 31 percent, higher than the 25 percent recommended in the BSI report (SERC 2016). The medium chip feedstock was included in the BSI LCI model by excluding the test with the moisture content of 37 percent and only using one run with the chip moisture content of 25 percent. In addition, the feedstock dryer system was not functioning properly resulting in the feedstocks needing to be air dried. It is assumed that with sufficient time, for example allowing the feedstocks to air dry for one season, moisture contents lower than 25 percent wet basis (34% dry basis) could be achieved. In the end, five types of forest residue (species/contaminant/comminution method) were used in the LCA of biochar for the BSI machine (Table 6). Depending on the forest residue used, the BSI system required different quantities of input material. Table 7 shows the quantity of forest residue needed to produce 1 metric ton of biochar including residue needed for the Power Pallet.

Table 6 Woody feedstocks used in BSI the biochar LCI model

Species	Contaminant	Comminution method	Ash content	Moisture content (wet basis)	Moisture content (dry basis)
Conifer	None	Ground	1.68%	16.93%	20.39%
Conifer	2/3 bole, 1/3 tops	Ground	3.65%	16.20%	19.33%
Conifer	9% soil	Ground	11.45%	14.91%	17.53%
Conifer	none	Chip, medium	0.08%	25.18%	33.65%
Conifer	none	Chip, small	2.13%	20.66%	26.04%

Table 7 Forest residue requirements for the producing one metric ton of biochar with 5 different comminution and contaminant types.

	Residue consumption 1,000 kg biochar produced		
	Biochar	**Power Pallet**	**Total**
	kg of residue, (oven dry mass)		
Ground clean	6,550	387	6,937
1/3 tops:2/3 bole	6,781	407	7,187
Ground 9%	7,575	358	7,934
Chipped, med	8,392	439	8,831
Chipped, small	5,059	302	5,361
Average	6,871	379	7,250

Based on the SERC (2016) report, the BSI machine was using a diesel generator and later with a biomass gasifier (Power Pallet) (Photo 4) to generate the required energy to produce biochar. For the remote BCT locations, the LCI BSI model compared the diesel generator to the biomass gasifier. When the BCT location is in town, comparisons for production were made between the diesel generator, the biomass gasifier, and the use of grid electricity. Table 8 lists the input data used in the LCI model for each feedstock type. Propane was used for startup under all energy generation options. Table 7 also lists the different measurements of fixed carbon in the biochar. Fixed carbon in the biochar ranged from 58 to 83 percent (dry basis).

Photo 4 Power Pallet. Photo credit: All Power Labs

Table 8 Gate to gate LCI input data for each type of conifer feedstocks per metric ton of biochar produced. Diesel fuel or a biomass gasifier was used to generate the electricity demand. Input values are the gate-to-gate for biochar production only.

	Unit	Ground clean	Ground, 2/3 bole, 1/3 tops	Ground, 9% soil	Chipped, medium, clean	Chipped, small, clean
		Per 1 metric ton of biochar				
Fixed carbon	%	79	65	58	83	60
Feedstock[1/] Input, dry basis	kg	6,937	7,187	7,934	8,831	5,361
Biochar output	kg	1000	1000	1000	1000	1000
Efficiency	%	0.16	0.16	0.14	0.13	0.21
Gasifier input	kg	387	406	359	462	302
Diesel	L	121	110	158	206	169
Electricity	kWh	223	234	207	266	174
Propane	L	3,005	1,727	1,037	7,760	4,578

1/ Includes required biomass for running the Power Pallet

6.2 Oregon Kiln

Production input data for the Oregon Kiln used in this analysis is based on several pilot projects using the kilns that have been conducted by Wilson Biochar Associates (Wilson 2015). We were not able to measure conversion efficiency on a dry weight basis, so we took the figure for a steel pyramid kiln using 50% wood and 50% eupatorium (woody brush) from Table 1 in Cornelissen et al. (2016) Emissions data were taken from the same reference, Table 3. Biochar quality data is provided by Wilson Biochar Associates and Gabilan Laboratory.

The scenario used for our LCI model is based on a stewardship contract on the Umpqua National Forest by South Umpqua Rural Community Partnership (www.ubetbiochar.blogspot.com) that was completed in October 2017. We assumed a crew of 6 people would operate 12 Oregon Kilns along a forest roadside where feedstock was piled. Tables 9 and 10 give the input parameters for the operation of the Oregon Kiln (cradle-to-gate) used in the LCI model.

6.2.1 *Feedstocks Preparaton*

Oregon Kilns are lightweight (less than100 kg) and mobile, allowing several kilns to be located on the roadside with transportation of residues to the roadside. Residues are cut to a maximum 4-foot length using chain saws and piled to dry. Care must be taken not to compact the feedstock or push dirt into piles, since they must be taken apart by hand for hand loading into kilns. An excavator with a grapple loader is good for this purpose since it can lift and drop feedstock without having to push it over the ground where it can collect dirt.

Table 9 Fuel requirements for cradle-to-landing feedstock preparation for production of one metric of biochar

Equipment	Manufacturer	Size	Fuel consumption rate	Used for
Chain saw			0.24 L/ton	Cutting biomass to length
Feller Buncher			0.77 L/ton	Harvesting/Hauling

6.2.2 *Biochar Production*

Biochar quality produced in the Oregon Kiln can vary according to feedstock species, moisture and ash content. However, the degree of carbonization and percentage of fixed carbon is usually high. This occurs because of the high temperature below the flame where pyrolysis takes place – about 680 to 750 degrees C (Cornelissen et al. 2016) and the long residence time of feedstock in the kiln due to the nature of the production process. The process can be characterized as a continuous batch system: while new feedstock is continually added, the biochar is only emptied from the kiln when it is full and the batch is completed. This results in a long residence time in the hot zone of the kiln and hence a fully carbonized biochar is generally produced.

The gate-to-gate LCI parameters for the Oregon kiln are very minimal due to manual loading and unloading of the kilns (Table 10). Propane is used for the startup of the kiln.

Table 10 Gate-to-gate LCI input data for one metric ton of biochar produced using the Oregon kiln. Includes feedstock preparation and handling. Emissions are for onsite only, no upstream emission for the use of fuels included.

	Unit	Forest Residues
Fixed carbon	%	76
Feedstock input	kg	5,000
Propane	L	1,020
Water (for quenching)	L	2,000

6.3 Air Burner

The production data used in the Air Burner model is based on several days of operation using an Air Burner S-220 unit on the Siskiyou National Forest in May 2016. The unit was used to process mostly fresh, green slash. Although the purpose for using the unit was slash disposal through incineration, it produced several large batches of char as a byproduct. The production input data used in this analysis is based on those operations. Data was provided by Jack LeRoy of Forest Energy Group, the contractor hired to run the machine. Since the Air Burner would be operated in a similar manner to the Oregon Kiln, we consider it as a scaled-up version of the smaller kiln, and we use the same emissions data and production efficiency from Cornelissen et al. (2016). Due to the refractory insulation in the Air Burner, it operates at a higher temperature than the Oregon Kiln. We would expect that the biochar produced would have a higher percentage of fixed carbon since it was made at a higher temperature. Laboratory analysis of a biochar sample from the Air Burner found that it had 89 percent fixed carbon, as compared to the Oregon Kiln sample which had only 76 percent fixed carbon.

6.3.1 *Forest Resources*

All data used for the Air Burner feedstock input for biochar production system was based on the same scenarios described for the BSI unit excluding chipping or grinding of the residue (Figure 9). It begins with the collection of the biomass using traditional harvesting mechanisms, moving the biomass to a landing or to a BCT site, and ending with finished marketable biochar.

6.3.2 *Biochar production*

The Air Burner is loaded with an excavator. To avoid equipment idle time, one excavator can service more than one Air Burner, depending on how far the machine must travel to reach the feedstock and how much feedstock sorting is needed (in the test run on the Siskiyou NF, the feedstock had a large amount of dirt contamination and the excavator was used to pick up the material and shake the dirt out of it). Our model uses only one Air Burner. Normally, in incineration mode, the Air Burner uses a diesel-powered blower continuously throughout its operation. However, in pyrolysis mode, using dry feedstock, we assume no use of the blower. Wetter feedstocks might perform better with some use of the blower to raise the temperature in the unit and help dry the feedstock, giving this unit considerable flexibility for processing feedstocks in different conditions. The Air Burner, like the Oregon Kiln is a batch process, and at the end of the batch, the unit must be unloaded and quenched. It is not possible to flood water into the unit because the sudden temperature change would crack the refractory material used to insulate it. Instead, the box must be lifted with the excavator and dragged forward to allow the biochar to fall out of the open bottom. At that point, it is quenched using water while the biochar is spread out to cool using a skid steer loader. Table 11 gives the production parameters and assumptions used in the Air Burner model.

Table 11 Gate-to-gate LCI input data for one metric ton of biochar produced using an Air Burner. Includes feedstock preparation and handling. Emissions are for onsite only, no upstream emission for the use of fuels included.

	Unit	Forest Residues
Fixed carbon	%	89
Feedstock input	kg	5,000
Propane	L	441
Water, for quenching	L	2,000

6.4 Biochar Quality

Biochar quality data is provided by Wilson Biochar Associates for the Air Burner and Oregon Kilns. The Air Burner results was obtained from a biochar sample produced during the Air Burner operations in the Siskiyou National Forest in May 2016. Residue demand and production efficiencies for each production system and residue type is given in Table 12. The BSI system had an average a 15 percent, with the highest reaching 20 percent from small chips. Both the Air Burner and the Oregon Kiln had assumed efficiencies of 20 percent (Cornelissen et al. 2016).

Biochar quality is measured in percent fixed carbon of the biochar. For the BSI system, an average fixed carbon in the biochar was 69 percent over all feedstocks. For the BSI unit, these varied from 58 to 83 percent depending on the forest residue used (Table 13). It was assumed only one type of residue was used for the Air Burner and the Oregon Kiln. Analysis of biochar from each of these systems was measure at 76 and 89 percent for the Oregon Kiln and Air Burner, respectively (Table 13).

Table 12 Residue use for production of one metric ton of biochar and biochar production efficiency for each biochar production system and residue type.

	Residue consumption per 1 metric ton biochar			Efficiency		
	BSI	**Air Burner**	**Oregon Kiln**	**BSI**	**Air Burner**	**Oregon Kiln**
		Metric ton				
Ground clean	6.6			15%		
1/3 tops:2/3 bole	6.8	5.0	5.0	15%	20%	20%
Ground 9%	7.6			13%		
Chipped, med	8.4			12%		
Chipped, small	5.1			20%		
Average	6.9	5.0	5.0	15%	20%	20%

Table 13 Biochar quality as measured by percent fixed carbon in the biochar for each Biochar production system and residue type.

	Biochar Quality		
	Biochar	Oregon Kiln	Air Burner
	% Fixed Carbon in Biochar		
Ground clean	79%		
1/3 tops:2/3 bole	65%	76%	89%
Ground 9%	58%		
Chipped, med	83%		
Chipped, small	60%		
Average	69%	76%	89%

6.5 Emission Factors

Emission results initially obtained from SERC (2016) reported high levels of CO, propane, NOx, and SO2 and indicated that these emissions could likely be over the threshold of the sensors. In the initial testing of the machine, there were problems with maintaining the flow rate of oxygen into the flare (Figure 3) resulting in incomplete combustion and high levels of CO, propane, NOx, and SO2, and low levels of CO2. They concluded that emissions can be mitigated by increasing the size of the flare. Making adjustments in the flow rate of oxygen, and using a dual auger system to increase production and efficiencies, a subsequent test in 2016 was made using medium chips in the BSI machine (Severy et al. 2017). The emission factors for this run are reported in Table 14 along with emissions factors for the slash pile burning, the Oregon Kiln, and an Air Burner. For the second BSI test, CO emissions were lowered due to more complete combustion. Carbon monoxide and unburned hydrocarbons (propane) were converted to CO2. Carbon dioxide and biogenic emissions increased. Slash pile burn emissions were obtained from Oneil et al., 2017 and the Oregon Kiln and Air Burner factors were taken from Cornelissen et al., 2016. The new emission factors measured for the BSI unit were applied to the original feedstock flow rate even though these rates changed, and higher efficiencies were achieved in the 2017 test (Severy et al. 2017).

Table 14 Emission factors used in the LCA. Factors are reported in kg per kg of forest residue (oven dry basis) used.

	Slash Pile	Air Burner	OR Kiln	Power Pallet	BSI					
Comminution methods	NA	NA	NA	Chipped Medium		Ground			Chipped Small	Chipped Medium
Type of Forest Residue	Tops + Pulpwood	Tops + Pulpwood	Tops + Pulpwood	Pulpwood, clean	BSI Ave	Pulpwood, 9% Contaminant	1/3 Tops 2/3 Pulpwood	Pulpwood, clean	Pulpwood, clean	Pulpwood, clean
	Emission Factors, kg / kg of feedstock used									
Ammonia	4.80E-04									
Carbon dioxide, biogenic	1.69E+00	7.80E-01	7.80E-01	1.75E+00	2.19E+00	2.61E+00	1.90E+00	1.60E+00	3.25E+00	1.57E+00
Carbon monoxide, biogenic	6.53E-02	2.60E-03	2.60E-03	2.56E-02	6.98E-04	7.24E-04	5.25E-04	5.84E-04	9.64E-04	6.92E-04
Formaldehyde	1.04E-03									
Hydrocarbons, unspecified	4.08E-03									
Methane, biogenic	4.54E-03	2.60E-03	2.60E-03		1.52E-04	1.58E-04	1.15E-04	1.27E-04	2.10E-04	1.51E-04
Methanol	6.50E-04									
Nitrogen monoxides	0.00E+00	1.40E-04	1.40E-04	6.45E-04						
Nitrogen oxides	2.50E-03	1.44E-04	1.44E-04	1.56E-05	1.96E-03	2.04E-03	1.48E-03	1.64E-03	2.71E-03	1.95E-03
NMVOC, non-methane volatile organic compounds	5.55E-03									
Particulates, < 10 um	4.40E-03	1.28E-03	1.28E-03		1.38E-03	1.43E-03	1.04E-03	1.15E-03	1.90E-03	1.37E-03
Particulates, < 2.5 um	3.90E-03				1.22E-05	1.27E-05	9.19E-06	1.02E-05	1.69E-05	1.21E-05
Particulates					1.15E-03	1.19E-03	8.66E-04	9.63E-04	1.59E-03	1.14E-03
Propane				2.62E-04	4.19E-04	4.34E-04	3.15E-04	3.50E-04	5.78E-04	4.15E-04
Soot	2.80E-04									
Sulfur dioxide	8.30E-04			1.07E-04	3.49E-05	3.62E-05	2.62E-05	2.92E-05	4.82E-05	3.46E-05
TOC, Total Organic Carbon	2.11E-03									

7 LCA RESULTS

Life cycle impact assessment results are presented for:

- GWP - Biochar production by forest residue type
- GWP – Biochar production at remote site versus transporting to town
- GWP – Biochar production by different production system
- GWP w/ biogenic carbon for biochar production systems with "slash and burn" comparisons
- GWP – Biochar production systems by life cycle stage (residue preparation, biochar production)
- Selected impact categories reported for each production system and production stage.

Unless otherwise noted, carbon neutrality was assumed, carbon emissions released during biochar production are equal to the CO2 absorbed during tree growth. The amount of carbon as CO2 eq. is reported for what is stored in the biochar. Taking the production emissions and the carbon storages, net carbon emissions are reported. In the case of comparisons with slash and burn, carbon neutrality was not assumed. In this case, production emission is reported as a positive, and carbon uptake during tree growth and carbon content of biochar are a negative to the system. The resulting net carbon emission is the sum of these.

7.1 BSI Production System – Remote BCT site

The BSI unit was tested with various types of forest residues (Table 15) and was powered at the remote site by either a diesel generator or biomass gasifier (Power Pallet). The Power Pallet provided an improvement in GWP over all forest residue types. Medium chipped pulpwood had the highest GWP emission with both power sources, where ground tops and ground pulpwood produced the lowest. When carbon storage or biochar quality is considered, medium chipped pulpwood stores the most fixed carbon in the biochar and subsequently has the lowest net carbon emission of -619 kg CO2 eq., meaning it stores nearly 3 times of what is emitted (Figure 11). Using the Power Pallet provides a significant improvement in net GWP over the diesel generator, for all residue comminution methods and contaminate levels, despite the extra feedstock processing necessary for generating electricity from the Power Pallet.

Table 15 Global warming potential, kg CO2 eq., for remote biochar production using the BSI machine.

GWP kg CO2 eq / 1,000 kg of biochar	Pulpwood - Chipped Small	Pulpwood- Chipped Medium	Pulpwood, Ground, Clean	Pulpwood, 9% Contaminant - Ground	1/3 Tops 2/3 Pulpwood- Ground
Power Pallet					
kg CO2 eq. emission, production	163	211	177	205	178
kg CO2 eq. stored in biochar	-600	-830	-790	-580	-650
kg CO2 eq emission, net	-437	-619	-613	-375	-472
Diesel					
kg CO2 eq. emission, production	690	852	553	695	518
kg CO2 eq. stored in biochar	-600	-830	-790	-580	-650
kg CO2 eq emission, net	90	22	-237	115	-132

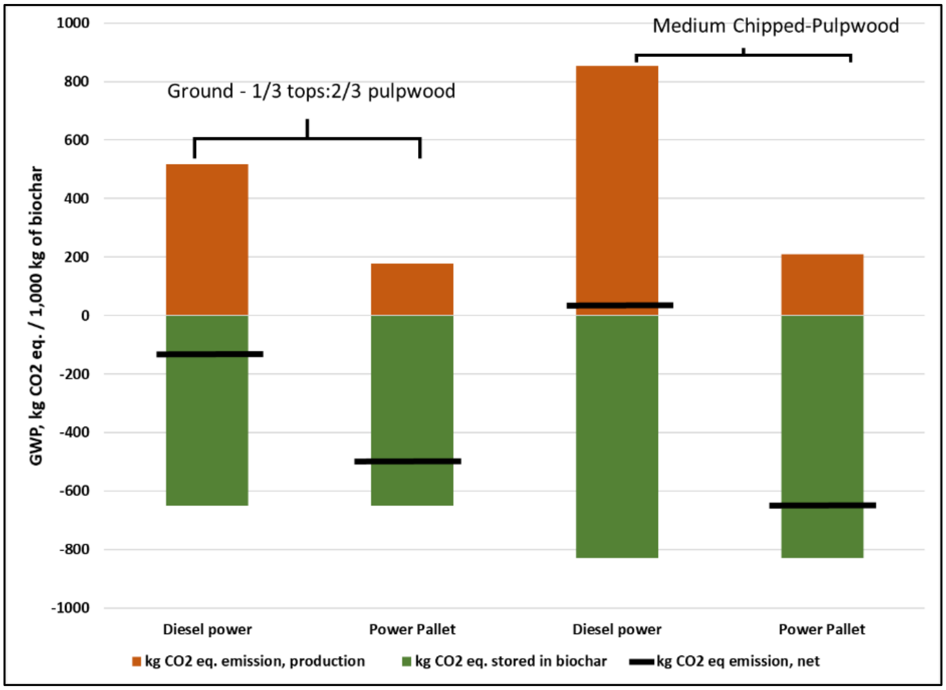

Figure 11 Remote BCT production of biochar using the BSI system. All feedstock preparation activities and biochar production take place at the landing.

7.2 BSI Production System – In-Town BCT site

Transporting the forest residue two hours to a town BCT location resulted in a 34 percent increase in GWP when the Power Pallet was used compared to the remote production of biochar (Table 16). If the diesel generator is used, the difference was only 9 percent. In-town production of biochar did provide the opportunity to use grid electricity. Using grid electricity to operate the BSI machine produced a 53 percent decrease in GWP from the diesel generator used at a remote BCT site, but had an 88 percent increase over a remote BCT with Power Pallet. Again, GWP increased for production of biochar when the material was transported 4 hours from the landing compared to a 2-hour transport. These were most pronounced when the Power Pallet was used, 43 and 40 percent for medium chips, and ground 1/3 tops:2/3 pulpwood, respectively. When the diesel-powered generator was used for biochar production, difference between a 2- and 4-hour haul distance, produced differences of 13 and 15 percent for medium chips and ground 1/3 tops:2/3 pulpwood, respectively. It appears that the availability of using a grid electricity had little benefit over the Power Pallet when a town BCT site was used. In-town grid electricity used for biochar production resulted in a 46 percent increase in GWP over the Power Pallet for ground 1/3 tops:2/3 pulpwood and 40 percent with medium chips at a 2-hour haul distance. Grid electricity did have a significant improvement in carbon emissions over the use of a diesel generator for both a 2- or 4-hour haul distance.

Table 16 Global warming potential, kg of CO2 eq. per one metric ton of Biochar, when produced at a remote location and residue haul distances of 2 and 4 hours.

GWP kg CO2 eq / 1,000 kg of biochar	Pulpwood-Chipped Medium			1/3 Tops:2/3 Pulpwood- Ground		
	Remote	2-hour	4-hour	Remote	2-hour	4-hour
Electricity	NA	397	513	NA	336	422
Diesel	852	921	1037	518	566	652
Power Pallet	211	283	406	178	230	322

Further comparisons on net carbon emission were made between the remote location and hauling the residue to a town BCT site. Figure 12 represents the net carbon impacts of producing biochar within a 2-hour haul distance from the landing. In the transportation scenarios, pulpwood is hauled as logs and chipped or ground at the BCT site (Figure 10). All other forest residues are ground at the remote site before transported to in town BCT site location. For comparison between remote and town BCT sites, only the medium chipped pulpwood and ground 1/3 tops:2/3 pulpwood feedstock types were used. These two feedstocks represent a percent fixed carbon of 83 and 65 for medium chipped pulpwood and ground 1/3 tops:2/3 pulpwood, respectively and best represent forest residues collected and comminution methods that likely would be used. For the remote location and 2-hour transportation distance to a town BCT site, all scenarios except biochar produced from medium chips and fueled by diesel had net negative CO2 eq. emission (Figures 11 and 12). Once the ground residue or pulpwood is transported 4 hours and diesel fuel for biochar production energy there is more carbon is emitted from collection, production, and transport than is stored in the biochar (positive net GWP)(Figure 13).

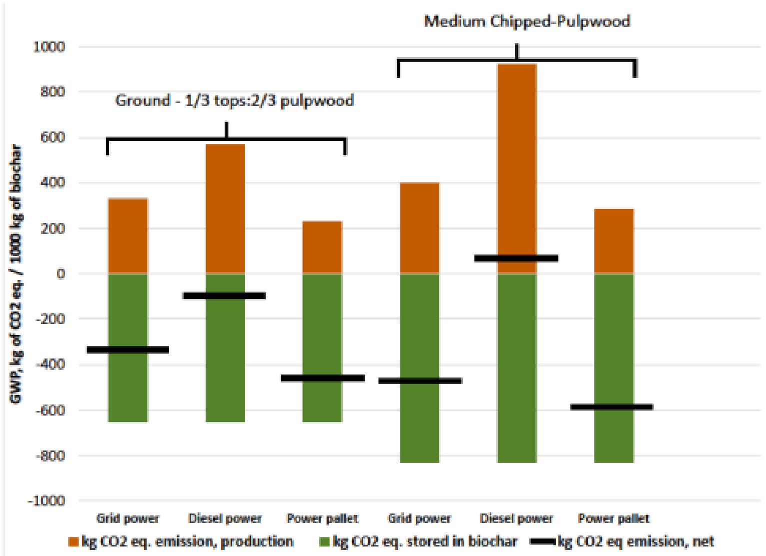

Figure 12 In-town BCT production of biochar using the BSI system. Feedstocks were transported a maximum of 2 hours from the landing.

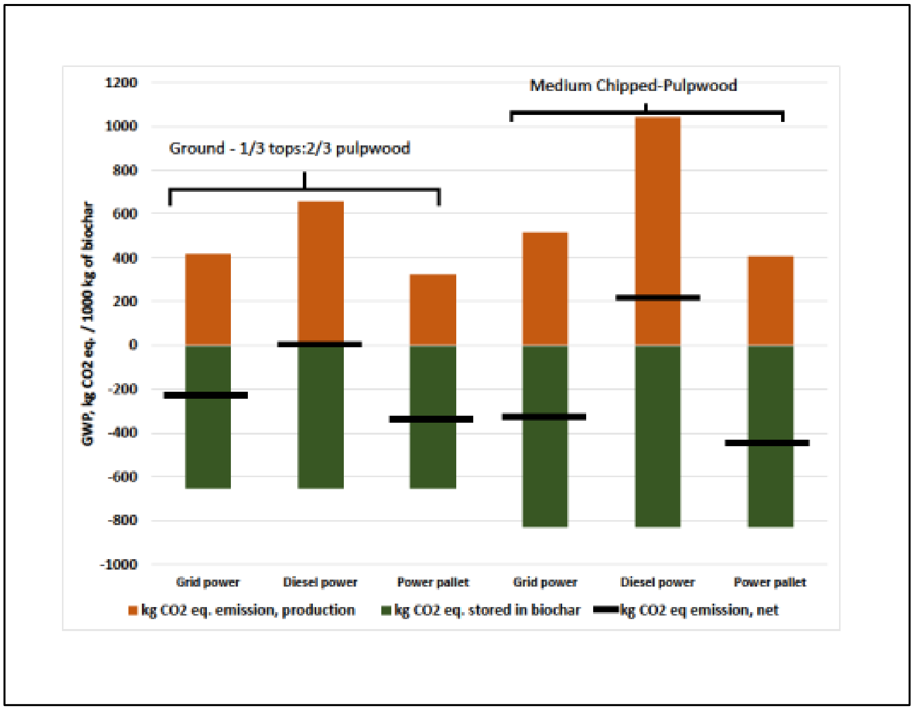

Figure 13 In-town BCT production of biochar using the BSI system. Feedstocks were transported a maximum of 4 hours from the landing.

7.3 BSI, Oregon Kiln, and Air Burner – Remote Site

Three types of biochar production systems were compared, the BSI unit, an Oregon Kiln, and an Air Burner. All these systems have been described in detail in earlier sections in this report. These systems were all compared at the remote site and included forest residue collection and preparation (hauling, cutting, grinding, and chipping), production of biochar, and fuel sources to operate. Production rates of biochar for the three systems were 240 kg/hr[2], 800 kg/hr[3], and, 275 kg/hr for the Oregon Kiln, Air Burner, and the BSI machine (average). The BSI low was 198 kg/hr for pulpwood chipped small and a high of 347 kg/hr for ground tops and pulpwood (SERC 2015). We felt a better comparison between biochar production systems was to scale the carbon emissions based on the biochar quality produced versus a metric ton of biochar produced. This would allow us to see the impact associated with biochar quality, as measured by percent fixed carbon in the biochar (Figure 14). Figure 14 shows the overall GWP, kg of CO2 eq., for each residue used in the BSI system, the Oregon Kiln, and the Air Burner. The GWP emissions in Figure 14 do not include emissions from biogenic carbon dioxide. There is general trend that GWP emissions decrease as the percent of fixed carbon in the biochar increase. Both the Oregon Kiln and the Air Burner have the lowest carbon emission due to not needing to grind or chip the feedstock. On

[2] One Air Burner will produce 800 kg of biochar per hour (based on loading rate of 4 bone dry metric ton feedstock per hour from Air Burner literature and 20% efficiency).

[3] One Oregon Kiln will produce 20 kg biochar per hour (Wilson Biochar Associates). The model uses 12 kilns, so total hourly production for the crew is 12x20=240 kg/hr.

the otherhand for these systems, the impact of biochar production proportional is higher due to lower impact for feedstock preparation.

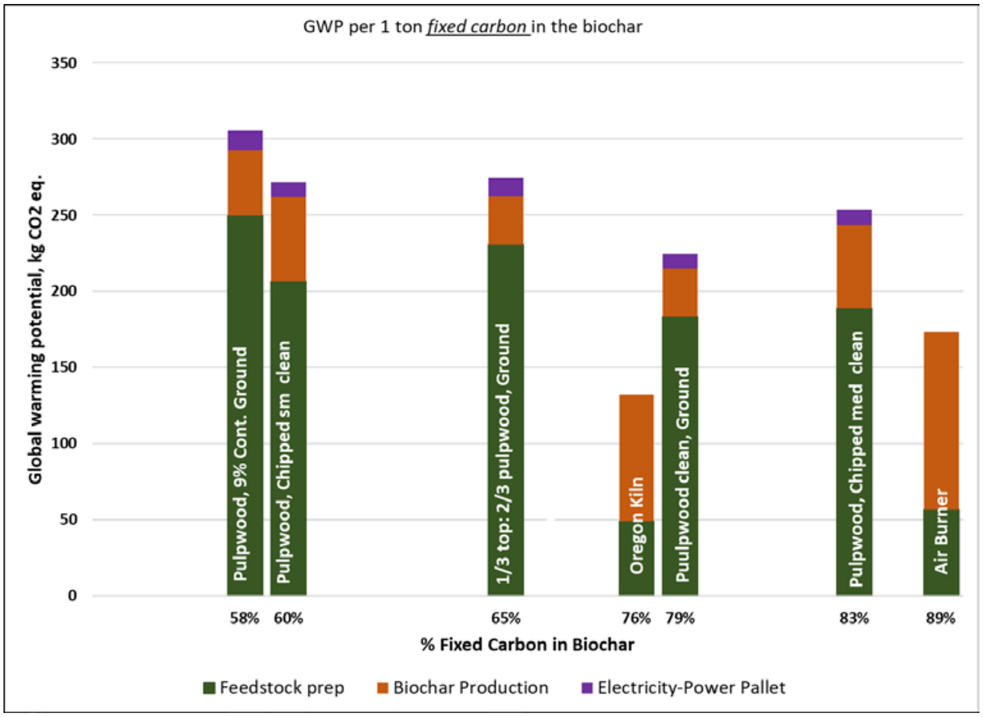

Figure 14 Global warming potential, kg of CO2 eq., for a metric ton of fixed carbon for various forest residues types and biochar production systems.

7.4 Biochar Production vs. Slash and Burn – Remote BCT site

Comparisons were made between the remote production of biochar using two residue types to a typical pile and burn operation of forest residues. The TRACI impact method was modified to consider all carbon dioxide emissions (biomass and fossil based). Carbon neutrality was not assumed. On the other hand, we did include the carbon dioxide that would have been absorbed during tree growth for the residues as well as the carbon, as CO_2, permanently stored in the biochar.

To fully understand the environmental impact of producing biochar at a remote BCT site, comparisons were made to the “business as usual” (BAU) practice of pile and burn the residues after a commercial harvest. Included in these comparisons, both the Power Pallet and the generator were used to produce biochar with the BSI machine. The Oregon Kiln and Air Burner were also included. Net GWP CO_2 eq. emissions for 1 metric ton of feedstock are -0.29, -0.63, -0.04, and -0.04 for biochar produced with ground tops and pulpwood, biochar produced with medium chips, burning tops and pulpwood, and burning pulpwood, respectively (Figure 15). The pile and burn options are nearly carbon neutral. The use of an Oregon Kiln and Air Burner produced less carbon emission and stored more carbon than the BSI scenarios. All biochar production systems had a net negative carbon emission, while the slash and burn scenarios were nearly carbon neutral (-0.04 mt CO_2 eq.) When a diesel generator is used, there is a 66 percent decrease in NET carbon storage for the tops/pulpwood biochar system and 14 percent decrease in biochar system that used chipped pulpwood (Table 17).

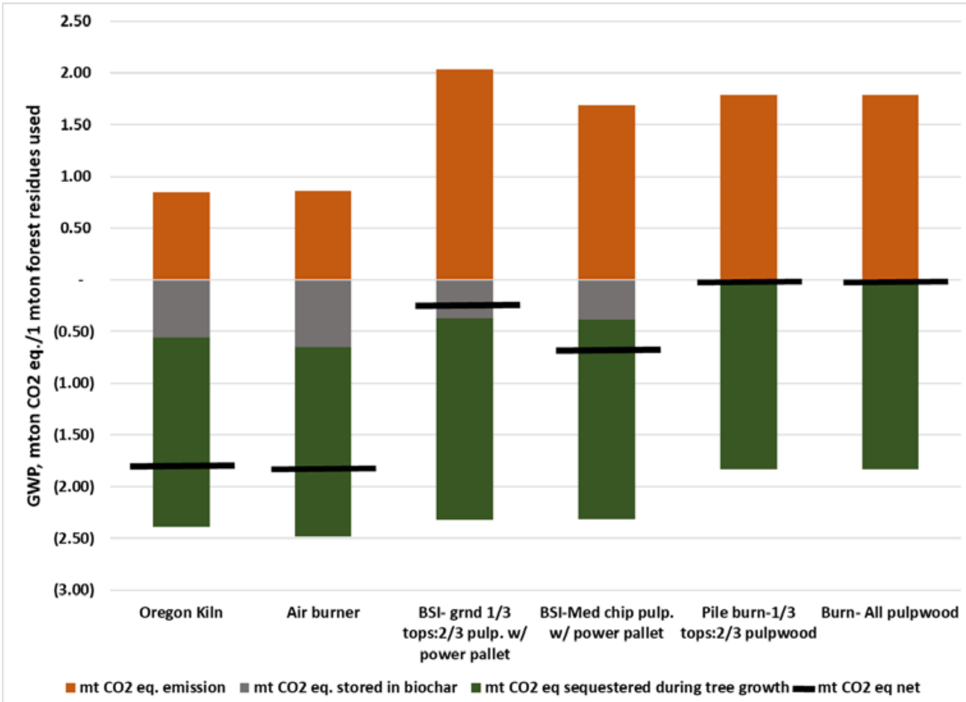

Figure 15 Net carbon impacts for biochar production at remote BCT compared to burning slash piles. GWP results are for 1 metric ton of CO_2 eq. per metric ton of biomass used/combusted. BSI production is with a Power Pallet.

Table 17 Net carbon impacts for biochar production at remote BCT compared to burning slash piles. GWP results are for 1 metric ton of CO_2 eq. per metric ton of biomass used/combusted. BSI production is with a diesel generator.

	Biochar Production				Slash Burn	
	Oregon Kin	Air Burner	BSI w/ diesel generator		Pile and Burn	
GWP, metric ton of CO2 eq. per metric ton of biomass combusted	Top, branches, and pulpwood	Tops, branches and pulpwood	1/3 tops: 2/3 pulpwood, ground	Pulpwood, chipped med.	1/3 tops: 2/3 Pulp wood	All pulp wood
mt CO2 eq. emission	0.84	0.86	2.10	1.67	1.79	1.79
mt CO2 eq. stored in biochar	(0.56)	(0.65)	(0.37)	(0.38)		
mt CO2 eq sequestered during tree growth	(1.83)	(1.83)	(1.83)	(1.83)	(1.83)	(1.83)
mt CO2 eq net	(1.55)	(1.63)	(0.10)	(0.54)	(0.04)	(0.04)

Because biochar contains carbon that was sequestered by removing carbon dioxide from the atmosphere, the outcomes demonstrate the extent to which biochar serves as a carbon sink, like wood products when they are in service. However, biochar is expected to be a more decay resistant and therefore a more recalcitrant form of carbon sequestration than wood products. It also has the co-benefit of reducing the need for fertilizer, improving moisture holding capacity of soils, and therefore is expected to increase tree growth when applied under conditions where moisture and soil fertility are limiting factors (Page-Dumroese et al. 2017).

The TRACI life cycle impact assessment method provides more than GWP impacts. Table 18 lists all impact categories for remote biochar production systems. From a feedstock preparation standpoint, grinding the residue uses more fuel than chipping with the micro chipper (small chips) needing 300 percent more diesel fuel. What we are seeing in Table 18, is primarily driven by feedstock quality and the efficiency of the BSI machine in the first testing. Table 19 is for the slash pile burning and is further explained in Oneil et al (2017), but show here to show her that despite the many challenges of producing biochar in remote locations, there are complementary benefits in providing long term storage of recalcitrant carbon. Those benefits can be measured by avoided emission from open burning (Table 19). Table 18 and 19 are not to be compared on is on a metric ton of biochar and the other a metric ton of feedstock.

Table 18 Environmental impact for production of 1 metric ton of biochar for different biochar production systems. (Biogenic carbon is NOT included in the GWP)

		BSI with Power Pallet					Other Systems	
Impact category	Unit	Pulpwood, Chipped small	Pulpwood, Chipped medium	Pulpwood, ground clean	Pulpwood, 9% contaminant, ground	1/3 Tops 2/3 pulpwood, Ground	Oregon Kiln	Air Burner
		Per metric ton of biochar						
Ozone depletion	kg CFC-11 eq	5.39E-09	6.85E-09	6.32E-09	7.32E-09	6.54E-09	1.35E-09	3.92E-09
Global warming	kg CO2 eq	163	211	177	205	178	86	144
Smog	kg O3 eq	380	461	321	445	306	49	76
Acidification	kg SO2 eq	11.29	13.76	9.62	13.15	9.17	1.71	2.55
Eutrophication	kg N eq	0.69	0.83	0.58	0.80	0.56	0.11	0.16
Carcinogenics	CTUh	1.99E-06	2.55E-06	2.31E-06	2.65E-06	2.38E-06	5.03E-07	1.42E-06
Non carcinogenics	CTUh	1.92E-05	2.47E-05	2.23E-05	2.55E-05	2.29E-05	4.88E-06	1.36E-05
Respiratory effects	kg PM2.5 eq	0.23	0.29	0.20	0.27	0.19	0.02	0.04
Ecotoxicity	CTUe	374.65	482.13	431.95	492.86	442.83	95.28	262.12

Table 19 Life cycle impact assessment categories for open burning of slash per and biochar production per metric ton of forest residue (biogenic carbon included in the GWP)

Impact category	Unit	Oregon Kiln	Air Burner	BSI PP Ground 1/3:2/3	BSI PP med chip	Burn 1/3tops:2/3pulp	Burn 100% Pulp
		Per metric ton of forest residue					
Ozone depletion	kg CFC-11 eq	1.30E-10	7.84E-10	1.03E-09	8.61E-10	5.83E-11	5.83E-11
Global warming	kg CO_2 eq	8.41E+02	8.57E+02	2.03E+03	1.69E+03	1.79E+03	1.79E+03
Smog	kg O_3 eq	8.33E+00	1.53E+01	1.15E+01	9.70E+00	9.78E+01	1.01E+02
Acidification	kg SO_2 eq	2.95E-01	5.10E-01	4.05E-01	3.68E-01	3.64E+00	3.75E+00
Eutrophication	kg N eq	1.84E-02	3.15E-02	2.21E-02	1.87E-02	1.77E-01	1.84E-01
Carcinogenics	CTU_h	4.90E-08	2.83E-07	3.73E-07	3.20E-07	1.63E-05	1.80E-05
Non carcinogenics	CTU_h	4.76E-07	2.72E-06	3.59E-06	3.10E-06	4.18E-07	4.40E-07
Respiratory effects	kg $PM_{2.5}$ eq	3.02E-03	7.30E-03	1.89E-02	2.21E-02	4.54E+00	4.92E+00
Ecotoxicity	CTU_e	9.34E+00	5.24E+01	6.95E+01	6.06E+01	3.67E+01	4.00E+01

8 CONCLUSIONS

Production of biochar using forest residues that would otherwise been burned in the forest can offset carbon emissions by having lower net carbon emissions and storing carbon for long periods of time in the soil. Although not modeled in this study, the avoided emissions and benefits of biochar added to forest soils could increase the carbon benefit of biochar production by increasing forest net primary production (NPP), forest resilience and resistance to drought.

The handling and comminution of the forest residues increase carbon emissions. Systems that can process bulk feedstock such as the Oregon Kiln and Air Burner offer alternatives to forest waste disposal with less fossil fuel input. These systems have few components and are more mobile as compared to the BSI machine, so they can be moved more often to different remote processing sites, reducing the need to haul material within the remote watershed unit. The Oregon Kiln system in particular, offers a viable alternative for sites where feedstocks are widely scattered and greater mobility is required to bring biochar conversion platforms closer to feedstocks. The Oregon Kiln and related systems may find their greatest utility with smaller forestry operations such those undertaken by small woodland owners clearing for fuel reduction or restoration projects. Remote BCT sites can reduce carbon emissions by eliminating the transportation of the feedstock. Although not modeled here, transportation of workers might lessen the carbon benefits of the remote location, particularly for the Oregon Kiln which requires a crew of 6 workers in the scenario modeled here. Both the Air Burner and the more mechanized BSI system require fewer workers than the Oregon Kilns.

Transportation of biomass feedstock is a major source of emissions and the reason for examining these remote operations in the first place. However, there could be an advantage in locating the operation in town where grid power is available. For the BSI system, using a portable biomass gasifier for power generation had lower carbon emissions over a portable diesel generator both at the remote BCT and in town. Grid electricity provided no carbon benefits over the biomass gasifier, but did lower carbon emissions over the diesel generator. If the biomass gasifier is used to provide electricity for the unit, then there is little advantage in moving the operation to town.

Temperature of operation in all the biochar systems has an impact on biochar quality. Higher temperature operations produce biochar with greater fixed carbon content resulting in greater reductions in GWP. The higher temperature operation of the Air Burner will always produce a higher quality biochar with more fixed carbon. Feedstock characteristics also contribute to the fixed carbon content of the biochar products. One point to make is one reason for using these systems for disposal of forest residues (waste material) is reduce fuel stocks in forest systems, but each in itself can produce a fire risks. Extreme care must be taken on when to operate these BCT systems as well as where best to place them. In town options could possibly offer less risk.

Feedstock variability has a large impact on both biochar quality and biochar production efficiency. Moisture, contamination, and ash content all reduce both quality and efficiency. For the most efficient operations, care should be taken to keep feedstocks clean and dry.

The comparative analysis of biochar production relative to open burning provides an answer to the question: To Burn or Not to Burn? The analysis shows that despite the many challenges of producing biochar in remote locations, there are complementary benefits in providing long term storage of recalcitrant carbon. If efforts are conducted on a landscape level, the opportunity could exist to generate real benefits from reducing fire risk by utilizing large amounts of waste wood. The avoided emissions are directly relevant to human health effects as well as impacting wildfire behavior. All biochar production systems had a net negative carbon emission, while the slash and burn scenarios were nearly carbon neutral. When a diesel generator is used, net carbon storage decreased depending on feedstock type.

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