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Life cycle assessment of biochar produced from forest residues using portable systems

Maureen Puettmann [a], Kamalakanta Sahoo [b, c, *], Kelpie Wilson [d], Elaine Oneil [e]

[a] WoodLife Environmental Consultants & Consortium for Research on Renewable Industrial Materials (CORRIM), United States
[b] Forest Products Laboratory, United States Forest Service, Madison, WI, 53726, United States
[c] Department of Biological Systems Engineering, University of Wisconsin-Madison, Madison, WI, 53706, United States
[d] Wilson Biochar Associates, United States
[e] University of Washington & CORRIM, United States

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A B S T R A C T

Forest fires are getting extreme and more frequent because of increased fuel loads in the forest and extended dry conditions. Fuel treatment (i.e., thinning) methods to mitigate forest fires will generate large volumes of forest residues together with available logging residues that can be used to produce biochar. It has been proposed that portable biochar systems are economical means to utilize forest residues as an alternative to slash burning. In this study, the environmental impacts of biochar produced from forest residues using three portable systems [1. Biochar Solutions Incorporated (BSI), 2. Oregon Kiln, and 3. Air-curtain Burner] were evaluated using a cradle-to-gate life-cycle assessment approach. Environmental impacts were analyzed considering the various quality of feedstock, biomass collection methods, different production sites, and various sources of power used in the production of biochar. The results illustrate that the global warming potential (GWP) of biochar production from forest residues through BSI, Oregon Kiln, and Air-Curtain Burner were 0.25–0.31, 0.11, and 0.16 tonne CO_2eq./tonne of fixed carbon in biochar respectively. Compared to pile burn, biochar production from forest residues with a portable system at the landing, reduced global warming potential (GWP) by 1.92–2.83, 2.7, and 1.9 tonnes CO_2eq./tonne of biochar through BSI, Oregon Kiln, and Air-Curtain Burner respectively. The Air-Curtain Burner and Oregon Kiln have minimal feedstock preparation, thus have lower environmental impacts than the BSI system. The BSI system requires feedstock preparation and power to operate the system. The use of the biomass-gasifier generator improved the environmental performance substantially (16–280%) compared with a diesel generator in biochar production. Overall, the net GWP in biochar produced (0.10–1.63 tonne CO_2eq./tonne of residues) from forest residues can reduce environmental impacts (2–40 times lower net CO_2eq. emissions) compared to slash burning.

1. Introduction

The most extensive forest management challenges in western forests today revolve around fire and watersheds. Forest fires are getting extreme and more frequent because of increased fuel loads in the forest and longer dry climatic conditions (Cook and Becker, 2017; Sahoo et al., 2019). 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). 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 (Sahoo et al., 2019). In the United States (US), forest fires cost lives and huge economic impacts. Forest residues left in the forest may increase the risk of wildfire and those need to be disposed of for the replanting of the harvested forest. Usually, forest residues are pile burned but it incurs a cost, creates air pollution, and large pile burning may alter soil thereby lowering site productivity for the residual trees for decades (Oneil et al., 2017; Page-Dumroese et al., 2010) and uncontrolled burning may lead to large wildfires. A study on the economic impact of wildfire reported that the direct cost for fire suppression, excluding property damage, reported costing $1.84 billion (Cook and Becker, 2017; Dale, 2009)]

* Corresponding author. Forest Products Laboratory, United States Forest Service, Madison, WI, 53726, United States.
E-mail address: kamalakanta.sahoo@usda.gov (K. Sahoo).

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and the indirect cost, such as adverse health impacts, can cost from \$76 - \$130 billion/year in the US(Fann et al., 2018)].

The main economic obstacle to use forest residues is the high logistics cost of collection and machinery (Mirkouei et al., 2017; Sahoo, 2017; Sahoo et al., 2016). Forest residues are spread across large areas, and thus incur high collection costs (Wright et al., 2008; Yazan et al., 2016). Furthermore, biomass transport and handling costs are high due to low bulk density, low energy density, and high moisture content (Parkhurst et al., 2016; Sahoo et al., 2018). Forest residues generated during commercial logging operations also present a fire risk that must be treated or removed (Page-Dumroese et al., 2017). Moreover, controlled burning forest residues also cause air pollution and other adverse human health impacts (Berrill and Han, 2017; Oneil et al., 2017). These residues are potentially available for bioenergy and bio-based products, including biochar.

Other than chipping for biomass energy, the main alternative for forest residue disposal is the current practice of incinerating residues onsite (i.e., burn piles), which can alter soil productivity, increase CO_2 emissions, and produce particulates (Oneil et al., 2017; 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 (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. The categories of avoided emissions from fossil energy, soil, or alternative biomass waste disposal methods were highly variable and dependent on specific scenarios.

Large scale biochar production using slow pyrolysis had been proposed as a viable option. Mobile systems have been proposed to lower the cost of transporting forest residues to industrial facilities (Berry and Sessions, 2018; Rosas et al., 2015; Sahoo et al., 2019). However, these studies mostly focused on the economics of biochar production and its supply chain and did not address the environmental impacts differences between large scale centralized operations and mobile units.

Using life cycle assessment (LCA), to illustrate the benefits of biochar production and use to mitigate carbon emissions and restore forest health, can be useful to the several stakeholders such as forest owners, policymakers, and the public when the direct and indirect cost of forest fires are considered.

There have been many studies reporting the LCA of biochar production. Most are difficult to compare based on the 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 the CO_2 eq. per oven dry ton (odt) of biomass feedstock was an appropriate functional unit for comparing different bioenergy systems. The functional unit, CO_2 eq. per odt of biochar product was best for comparing different 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 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. Lee et al. (2010) 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.

There is a handful of research on portable systems and most of them are related to producing bio-oil from biomass and bio-oil needs upgradation to produce transportable biofuels (Badger et al., 2010; Chen et al., 2018; Mirkouei et al., 2016; Polagye et al., 2007). Rosas et al. (2015) performed the LCA of a portable system that produces biochar from ripped vines wood and illustrated the significant reduction of emissions due to the transportation of biomass compared to a centralized system. Forest Service researchers (Bergman and Gu, 2014; Gu and 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 (Homagain et al., 2015; Hudiburg et al., 2011; Ramachandran et al., 2017). Various other biochar LCAs have looked beyond the direct carbon sequestration values of biochar to analyze the 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 (Muñoz et al., 2017; Pereira et al., 2016; Peters et al., 2015; Rosas et al., 2015; Wang et al., 2014).

Transportation sensitivities are often significant in both the feedstock logistics phase and the biochar distribution and application phase. Forest residues' quality such as moisture, ash, size and type of residues (i.e., main stem, tops, branches) has a significant impact on biochar quality and productivity in biochar production which had not been addressed by the previous studies (Inoue et al., 2011; Severy et al., 2016).

As part of the Waste to Wisdom (Bergman et al., 2018) study, this paper presents a cradle-to-gate life cycle assessment approach used to estimate the environmental impacts of producing biochar from forest residues using three portable systems [e.g., 1. Biochar Solutions, Inc. (BSI), 2. Oregon Kiln, and 3. Air-Curtain Burner) considering different production scenarios. For example, (i) biochar produced through the BSI system either near a forest or an in-town location (either 2 or 4 h of transport distance for feedstocks), (ii) biochar produced through the BSI system using different quality of feedstocks (chipped pulp-quality forest residues and ground forest residues), and (iii) biochar produced through the BSI system using different sources of power (grid connection for in-town locations and diesel or gasifier-based generator for near-forest locations). Oregon Kiln and Air-Curtain Burner were tested only at the near-forest locations. Impacts of biochar return to the soil on NPP (Net Primary Productivity) and the dynamics of soil carbon sequestration have been excluded from this 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.

2. Methods

2.1. 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 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). ISO 14040 and ISO 14044 standards were followed to conduct the life cycle assessments (ISO, 2006a, b). The SimaPro 8.5 software was used to develop the LCI models, and produce results and analysis.

The functional unit for biochar LCA for the three production systems is one metric ton (1000 kg) 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).

2.2. System boundaries

The system boundary for the LCA of biochar begins with the harvesting of biomass and ends with marketable biochar (Figs. 1 and 2). The production flow can differ slightly depending on the biochar production system used, the feedstock used, the site/locations of conversion, and the fuel used for energy. Fig. 1 shows the system boundaries of the BSI biochar production of biochar system. Where the Oregon Kiln and Air-Curtain Burner's system boundary and flow diagram is shown in Fig. 2. All three system boundaries included forest operations that include felling, yarding, loading, and some hauling of forest residues. Oregon Kiln and Air-Curtain Burner are assumed in this study to be used at near-forest site locations. The Oregon Kiln requires no comminution and can use tops, branches, and smaller pulpwood if less than 1.2 m in length and smaller diameter stems, preferably less than 15 cm. Air-Curtain

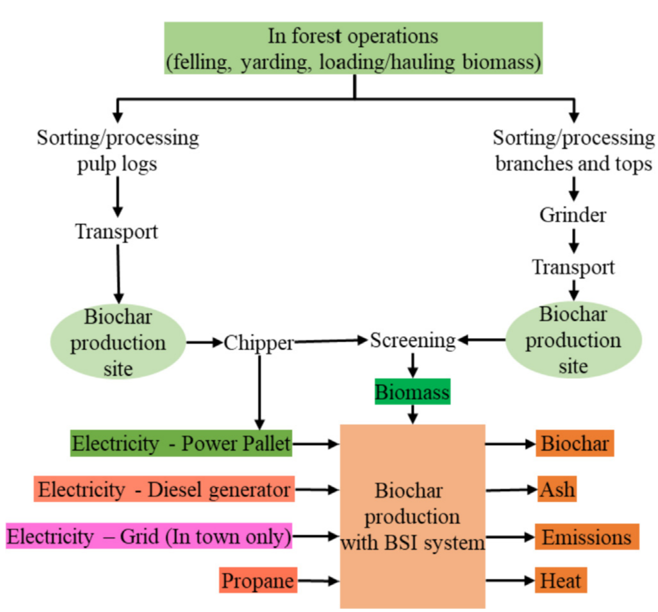

Fig. 1. System boundary for the production of biochar using the BSI system at either a remote or in town sites.

Burners can handle larger length and stem diameter biomass and do not require any preprocessing.

2.3. Description of biochar production systems

Biochar is produced from forest residues located at a remote site near the forest and at an in-town location using a maximum of 2 and 4 h of travel time from the forest (Fig. 3). For the BSI unit, forest residues are either ground in the forest transported by trucks or transported as whole logs and chipped at the in-town sites. The operation of the BSI biochar production system requires power which was supplied from either gasifier-based power pallet (wood chips to produce power), diesel generator or grid if available.

The Oregon Kiln and Air-Curtain Burner use uncomminuted forest residues but require reduction of length using chain saws or forest processors (Oneil et al., 2017; Wilson, 2017). Both of these production systems are used at the remote near forest location. They both require a small amount of fuel (i.e., propane) for the daily starting up the systems.

2.3.1. BSI (biochar systems incorporated) system

The BSI machine (Biochar Solutions, Inc.) is a mobile down-draft gasifier that uses chipped or ground feedstock, loaded into the top of the reactor (Fig. 4).

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 (or tonne) per hour (tonne/hr) or dry biomass (0.227 dry tonne/hr) and produce 0.045 tonnes/hr of biochar. The operation begins with the biomass feedstock loaded into the hopper (14). The 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 15.2 cm gap between them. The feedstock is loaded into the inner cylinder maintaining a bed depth between 46 and 122 cm. 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 details on the production of biochar using the BSI unit please refer to the Biochar Testing and Results Report (Severy et al., 2016).

The BSI system requires about 20 kW of power to operate. Grid connectivity for remote biochar production locations is rare. Therefore, a diesel generator or a biomass gasifier (Power Pallet) to generate the required energy to produce biochar at the remote biochar production locations. When the biochar production location is in town, comparisons for production were made between the diesel generator, the biomass gasifier, and the use of grid electricity.

2.3.2. Oregon Kiln

The Oregon Kiln consists of a simple truncated pyramid constructed of 14-gauge mild steel container with a solid bottom and a five-foot square top base known as a flame cap kiln (1.2 m^2 bottom base and a height of 0.6 m). The total capacity is 40 cubic feet (1.1 m^3). It is optimized for low-cost manufacturing and uses in

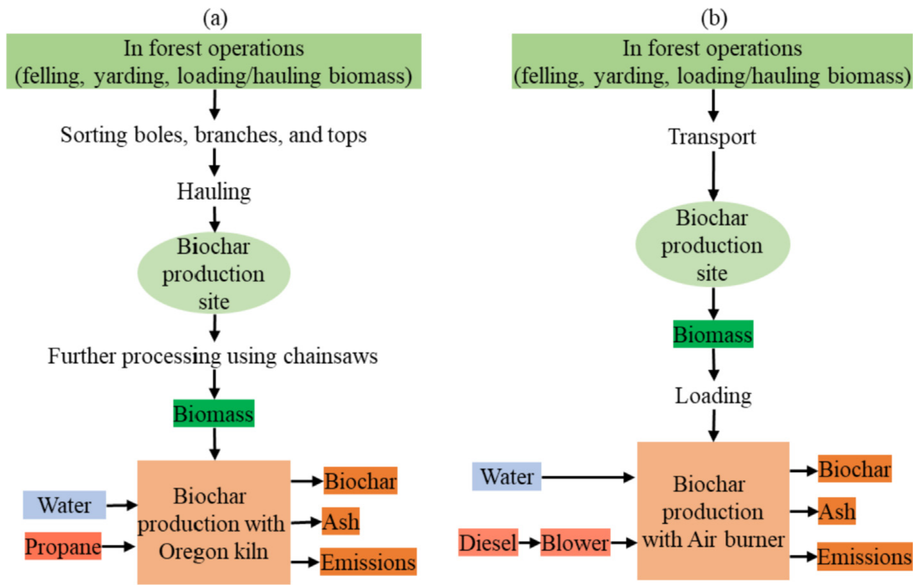

Fig. 2. System boundaries of production of biochar through (a) Oregon Kiln, and (b) Air-Curtain Burner.

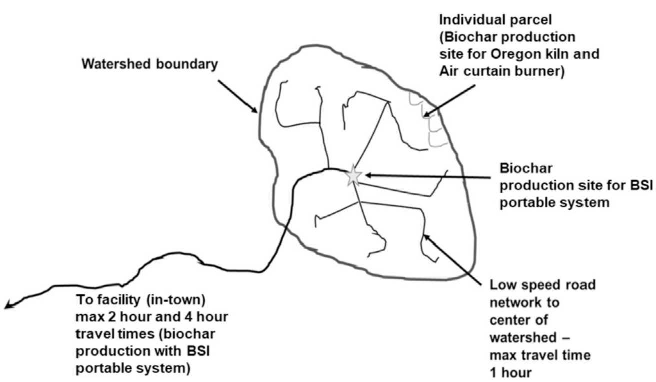

Fig. 3. Biochar production sites.

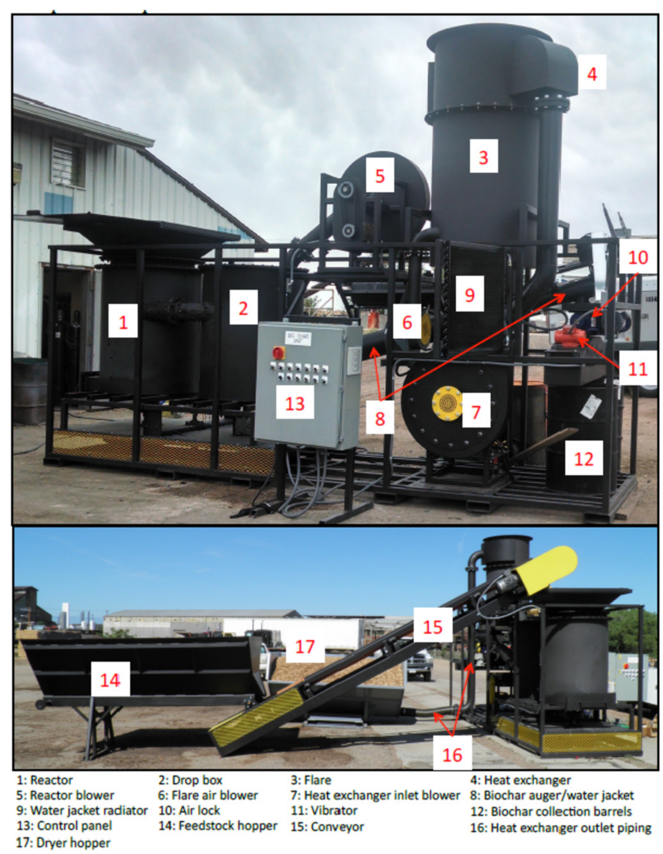

Fig. 4. BSI biochar production system. Image credit: Schatz Energy Research Center.

forest settings as an alternative to pile burning. 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 up to about 0.56 cubic meters (Wilson, 2017).

The Oregon Kiln was inspired by the “Smokeless Kiln” manufactured in Japan by the Moki Co. (Fig. 5). This cone-shaped kiln makes well-carbonized biochar with reported biomass to a char conversion efficiency of 13–20 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 char 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.

2.3.3. Air-Curtain Burner

An Air-Curtain Burner is a large, refractory-lined box equipped with a powerful blower that is used to incinerate biomass to ash. However, by changing some of the operating parameters, these units can be used to produce biochar. The S-220 model Air-Curtain Burner (Fig. 6) was used in this study which can be considered as a scaled-up version of the smaller kiln. Air-Curtain Burner’s operating procedure was similar to the Oregon Kiln. The frame size of approximately 9.2 m length, 2.6 m high and 2.6 m wide. A diesel engine of 36.5 kW was used to operate the fan. Due to the refractory

Fig. 5. Oregon Kiln operating in a forest setting. Images credit: Wilson Biochar Associates (wilsonbiochar.com).

Fig. 6. Air-Curtain Burner (1. Air manifold; 2. Air curtain; 3. Firebox refractory wall; 4. Wood waste or fuel; 5. Smoke and particulates. Image from www.airburners.com).

insulation in the Air-Curtain 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-Curtain Burner showed that it had higher fixed carbon, as compared to the Oregon Kiln.

The Air-Curtain Burner is loaded with an excavator. To avoid equipment idle time, one excavator can service more than one Air-Curtain 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-Curtain Burner. Normally, in incineration mode, the Air-Curtain Burner uses a diesel-powered blower continuously throughout its operation. The Air-Curtain 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.

2.3.4. Biomass harvesting and logistics and feedstocks preparation

This study used the forest residues generated from timberland during commercial logging operations based on the weighted average volume available from five regions in the state of California (Oneil et al., 2017). Forest residue collection and processing served as an input into the BSI, Oregon Kiln, and Air-Curtain Burner biochar production systems. All harvesting sites considered produced more than 22.4 odmt (oven-dry metric ton) biomass/ha, and of those sites, only 50 percent of the biomass is technologically accessible due to terrain, turnout limitations, and other biomass recovery limitations. Forest residues were segregated into pulp logs, and branches and tops. Hauling operations were separated into two distinct operations – one for pulp quality material and one for tops and branches. For the remote biochar production site (near-forest), haul time is limited to a maximum of 1 h from harvest sites. But for the in-town site, the hauling time is limited to a maximum of 2 and 4 h from harvesting sites to biochar production sites. For the 2- and 4-h haul distances to an in-town biochar production 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, whereas tops and branches were ground, screened, and loaded into the BSI unit.

According to the Schatz Energy Research Center report (Severy et al., 2016), the biochar machine successfully processed all feedstock types (Table 1) 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 (Severy et al., 2016, 2018). 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 (34%, dry basis) (Table 1). The average moisture content for the medium chip was 31 percent, higher than the 25 percent recommended in the BSI report (Severy et al., 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 residues (species/contaminant/comminution method) were used in the LCA of biochar for the BSI machine (Table 1). Depending on the forest residue used, the BSI system required different quantities of input material.

Logistics operations with unit operations to produce feedstocks for Oregon Kiln, and Air-Curtain Burner systems are shown in Fig. 2. For Oregon Kiln, forest residues are cut to a maximum 1.2-m 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 handloading 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.

2.4. Life cycle inventory

Data for the LCA of biochar was collected from a variety of sources and contained both primary and secondary data (Table 2). Operations inputs for biochar production including energy consumption, resource inputs, and biochar outputs were collected from actual operations for the BSI, Oregon Kiln, and Air-Curtain Burner units. Data for the LCA of biochar was collected from a variety of sources and contained both primary and secondary data (Table 2). It begins with the collection of the biomass using traditional harvesting mechanisms, transporting the biomass to a landing, processing the biomass, transporting to a biochar production site, further processing of biomass if needed, and ending

Table 1
Woody feedstocks used in BSI the biochar LCI model.

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

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

Data Type	Data source	Notes
BSI Biochar Machine	Schatz Energy Research Center (Severy et al., 2018), (Cornelissen et al., 2016)	Actual measurement
Air-Curtain Burner	Wilson Biochar Associates	Estimates from field experience
Oregon Kiln	Wilson Biochar Associates	Estimates from field experience
Forest Residue Collection and Hauling	Oneil et al. (2017)	
Slash emission factors	Oneil et al. (2017)	
Propane	LPG, combusted in industrial equipment/RNA	DATASMART 2016 [a]
electricity	Electricity, at eGrid, NWPP, 2008/RNA US	DATASMART 2016[a]
Diesel fuel	Diesel, combusted in industrial equipment NREL/US U	DATASMART 2016[a]
Gasoline	Gasoline, combusted in equipment NREL/US U	DATASMART 2016[a]

[a] Processes contained in the SimaPro Software. Pré Consultants, B.V. 2019. Simapro8.5.2 Life-Cycle Assessment Software Package, Version 36. Plotter 12, 3821 BB Amersfoort, The Netherlands. http://www.pre.nl/.

with finished marketable biochar. Forest residue collection and processing served as an input into the BSI, Oregon Kiln, and Air-Curtain Burner biochar production systems. 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). Several equipment configurations were modeled in the LCA on biomass recovery (Oneil et al., 2017). Equipment fuel consumptions are based on moving or handling or processing 1 dry tonne of forest residue. Table 3 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 biochar production site. Three locations were modeled for the biochar production: 1. Remote site at the landing; 2. Transportation distance of 2 h between residues and the in-town biochar production location; and 3. Transportation distance of 4 h between residues and the in-town biochar production location. 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.

The BSI system required electricity to operate which was supplied either by power pallet or diesel generator or grid electricity

Table 3
Diesel requirements for feedstock logistics (residue collection and handling, processing and transportation; Oneil et al., 2017) for production of one tonne of biochar.

	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

Table 4
Gate-to-gate LCI input data for each type of conifer feedstock per tonne of biochar produced.

Input resources	Units	BSI	BSI	BSI	BSI	BSI	Oregon Kiln	Air-Curtain Burner
		Ground, clean	Ground, 9% soil	Chipped, medium, clean	Chipped, small, clean	Ground, 2/3 bole, 1/3 tops	Ground, 2/3 bole, 1/3 tops	Ground, 2/3 bole, 1/3 tops
Feedstock	kg (dry)	6,937[a]/6,550[b,c]	7,934[a]/7,575[b,c]/	8,831[a]/8,392[b,c]	5,361[a]/5,059[b,c]	7,187[a]/6,781[b,c]	5000	5000
Biochar yield	%	16	14	13	21	16	20	20
Power pallet input	kg	387[a]/0[b,c]	359[a]/0[b,c]	462[a]/0[b,c]	302[a]/0[b,c]	406[a]/0[b,c]		
Diesel	L	121[b]/0[a,c]	158[b]/0[a,c]	206[b]/0[a,c]	169[b]/0[a,c]	110[b]/0[a,c]		
Electricity (from grid)	kWh	0[a,b]/223[c]	0[a,b]/207[c]	0[a,b]/266[c]	0[a,b]/174[c]	0[a,b]/234[c]		
Propane	L	3005	1037	7760	4578	1727	1020	441
Water (for quenching)	L	NA	NA	NA	NA	NA	2000	2000
Output products[d]	Units							
Biochar	kg	1000	1000	1000	1000	1000	1000	1000
Fixed carbon	%	79	58	83	60	65	76	89

[a] Include wood chips required to operate power pallet (gasifier-based electricity) to produce electricity for BSI unit.
[b] Diesel generator is used to produce electricity to operate BSI unit.
[c] Grid electricity is used to operate BSI unit.
[d] Emissions are mentioned in Table 5.

(Table 4). Small amounts of propane were needed for start-up for all biochar production systems (Table 4). Biochar quality (fixed carbon) produced can vary according to feedstock species, moisture and ash content (Severy et al., 2016). However, the degree of carbonization and percentage of fixed carbon is usually high in Oregon Kiln and Air-Curtain Burner. This occurs because of the high temperature below the flame where pyrolysis takes place – about 680–750 °C (Cornelissen et al., 2016) and the long residence time of feedstock in the kiln due to the nature of the production process.

The emissions generated from the slash pile burning and biochar production through the BSI system, Oregon Kiln, and Air-Curtain Burner are reported in Table 5. These emissions values were used in the LCI for each biochar production system and are included in the life cycle impact assessment results. Slash pile and burn is included for comparison of different scenarios for forest residue disposal.

2.5. Life cycle impact assessment

The life cycle impact assessment (LCIA) phase establishes links between the life cycle inventory results and potential environmental impacts. The LCIA calculates impact indicators, such as global warming potential and smog. 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 below. Environmental impacts are determined using the TRACI method (Bare, 2011). 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. Additionally, the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

For the purpose of this paper, only the global warming potential (GWP) impact category is presented. Unless otherwise noted, carbon neutrality was assumed; biogenic carbon emissions released during biochar production are assumed to be equal to the CO2 absorbed during tree growth. Net carbon emissions are reported by taking the carbon released during production (fossil-based) and the carbon stored in the biochar.

In the case of comparisons with slash and burn, carbon neutrality was not assumed. In this case, all carbon emission released during production is considered a positive, and carbon uptake during tree growth and carbon content of biochar are negative to the system.

3. Results

3.1. Biochar produced with the BSI system at remote sites

Based on the source of power (either diesel generator or power pallet), Fig. 7 shows the GWP of biochar production with the BSI unit at the near-forest site (remote) using different feedstocks as mentioned in Table 1.

The utilization of the power pallet provides a significant improvement in net GWP over the diesel generator over all residue comminution methods and contaminate levels, despite the extra feedstock processing necessary for generating electricity from the power pallet. Medium chipped pulpwood had a higher GWP production emission compared with ground residues. Biochar produced from medium chipped pulpwood stores the most fixed carbon and subsequently has a net carbon emission of −2832 kg CO_2 eq./tonne of biochar – storing nearly 14 times what is emitted

Table 5
Emission factors used in the LCA. Factors are reported in kg per kg of forest residue (oven-dry basis) used.

Comminution methods	Slash Pile Burn	Air-Curtain Burner	Oregon Kiln	Power Pallet	BSI					
	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	1/3rd tops +2/3rd pulpwood	Pulpwood, clean	Pulpwood, clean	Pulpwood, clean
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	–	–	–	–	–	–	–	–	–

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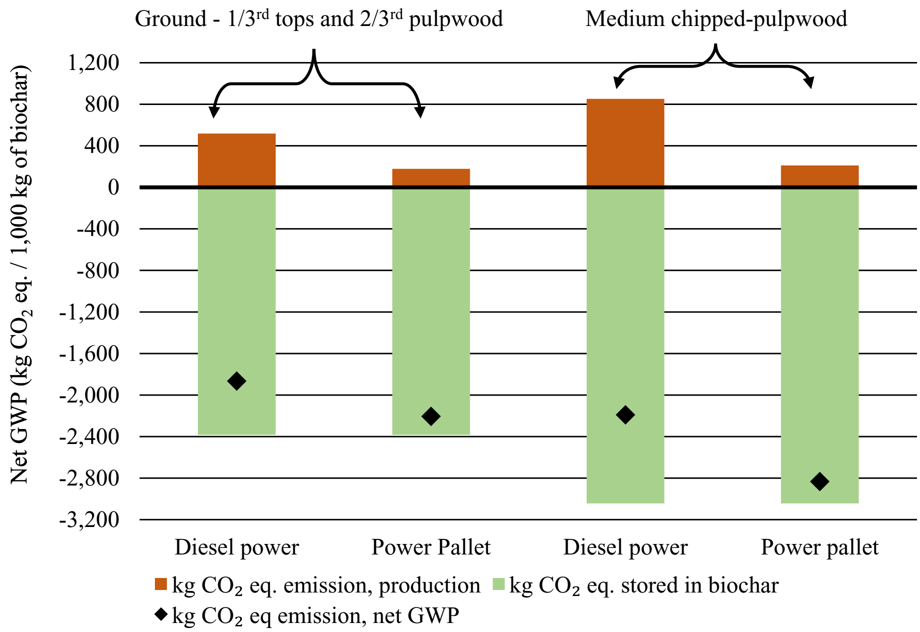

Fig. 7. GWP of biochar production using the BSI system at a remote biochar production site.

to produce biochar when using the power pallet.

3.2. Biochar produced with BSI system at the in-town sites

Transporting the residues to an in-town conversion site resulted in higher GWP values over the remote conversion site. For pulpwood transported and then chipped in-town resulted in 8–92% increase in GWP and for transporting ground (1/3rd tops and 2/3rd pulpwood) feedstock we saw a 9–81% increase in GWP (Table 6).

The 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 biochar production site but had an 88 percent increase over a remote biochar production site with Power Pallet. Again, GWP increased for the production of biochar when the material was transported 4 h from the landing compared to a 2-h 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, the difference between a 2- and 4-h 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 grid electricity had a little benefit over the Power Pallet when a town biochar production 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-h 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-h haul distance.

Fig. 8 shows the GWP of biochar produced with BSI unit from different types of forest residues at the 2-h haul distance in-town locations. The net GWPs of biochar produced from medium chipped pulpwood are higher than ground feedstock independent of power sources. Biochar production with the power pallet to operate the BSI system has the lowest GWP value and hence the highest negative net-GWP. With the increase in transportation distance of the feedstocks, the net reduction in GWP of biochar was reduced.

Table 6
Production emissions (kg of CO_2 eq./1000 kg of biochar) in biochar production at remote and in-town locations (residue haul distances of 2 and 4 h from forest to biochar production sites).

	Pulpwood-Chipped Medium			(1/3rd Tops and 2/3rd Pulpwood)- Ground		
	Remote	2-h	4-h	Remote	2-h	4-h
Electricity	NA	397	513	NA	336	422
Diesel	852	921	1037	518	566	652
Power Pallet	211	283	406	178	230	322

3.3. Biochar produced with BSI, Oregon Kiln, and Air-Curtain Burner at remote sites

Fig. 9 shows the GWP of three types of biochar production systems with respect to 1000 kg of fixed carbon in the biochar. The GWP emissions in Fig. 9 do not include emissions from biogenic carbon dioxide. In the case of BSI systems, about 80% of total GWP emissions are from feedstocks preparation and forest residues collection. While approximately 40% of total GWP emissions are the result of feedstocks preparation in both Oregon Kiln and Air-Curtain Burner systems. Both the Oregon Kiln and the Air-Curtain Burner have the lowest carbon emissions as these system does not require much feedstock preparation such as grinding or chipping and energy to run the systems. On the other hand, for these systems, the impact allocated to biochar production emissions is proportionally higher due to lower impact for feedstock preparation. Overall, GWP emissions decrease as the percent of fixed carbon in the biochar increases.

3.4. Biochar production vs. slash burn

Comparisons were made between the remote production of biochar using two residue types to a typical pile and burn operation of forest residues. In this case 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 (a part of this carbon dioxide absorbed was stored in the biochar).

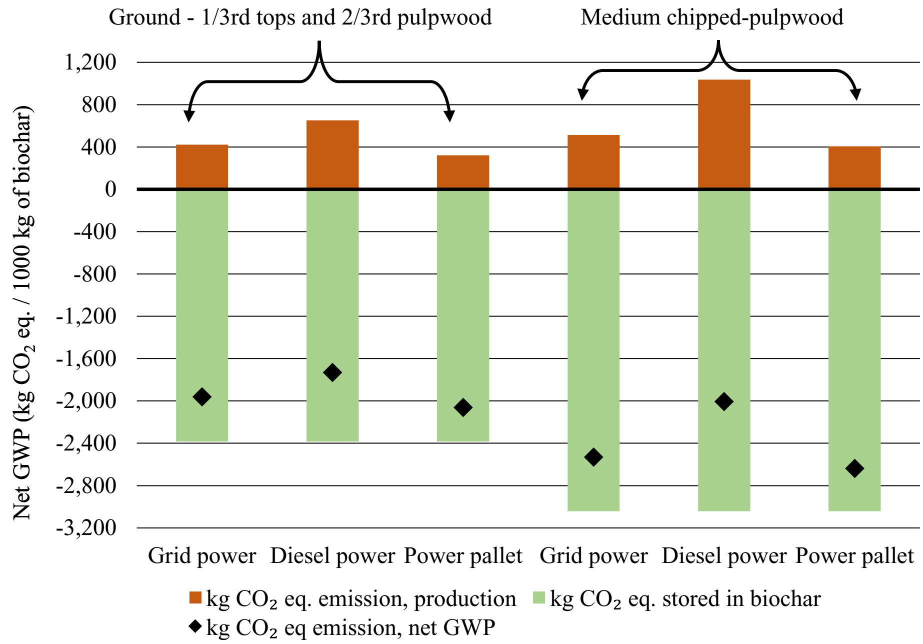

Fig. 8. In-town production of biochar using the BSI system (feedstocks were transported a maximum of 2 h from the landing).

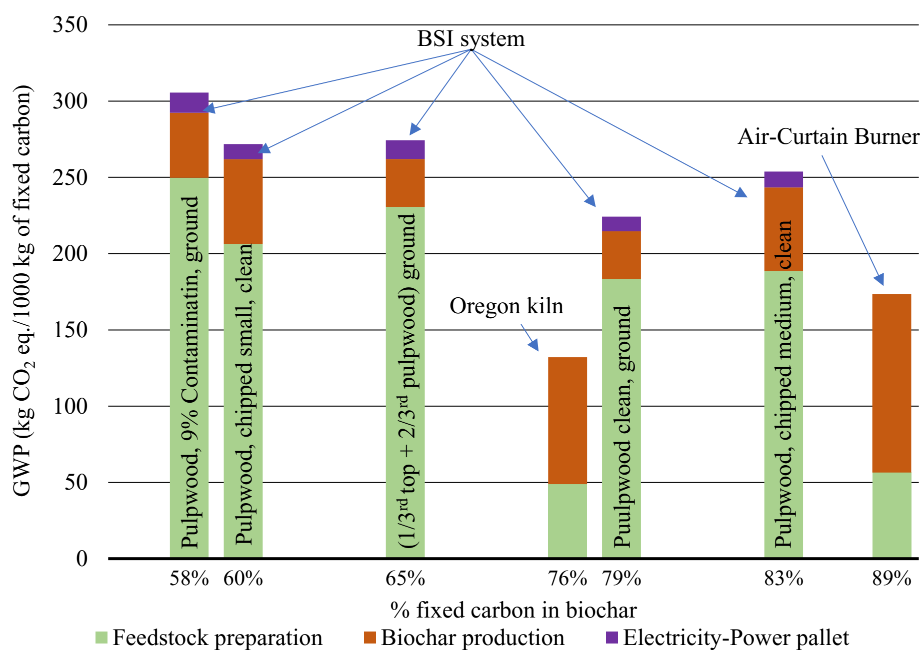

Fig. 9. Global warming potential, kg of CO_2 eq., for a metric ton of fixed carbon for various forest residues types and biochar production systems.

To further understand the environmental impact of producing biochar at a remote biochar production site, comparisons were made to the "business as usual" (BAU) practice of "pile and burn" of the residues after commercial harvest. Included in these comparisons, only the Power Pallet was used to supply electricity to operate the BSI machine in biochar production. Additional comparisons were made with Oregon Kiln and Air-Curtain Burner. Net GWP CO_2 eq. emissions for 1 metric ton of feedstock are 0.08, −0.25, 0.10, and 0.10 for biochar produced with ground tops and pulpwood, biochar produced with medium chips, burning tops and pulpwood, and burning pulpwood, respectively (Fig. 10). The pile and burn options are carbon positive. The use of an Oregon Kiln and Air-Curtain Burner produced less carbon emission and stored more carbon in the biochar they produced than the BSI machine scenarios. Except for BSI system with ground-feedstocks, biochar production systems had a net negative carbon emission, while the slash and burn scenarios were having net positive GWP (0.1 metric ton of 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 the biochar system that used chipped pulpwood (Table 6).

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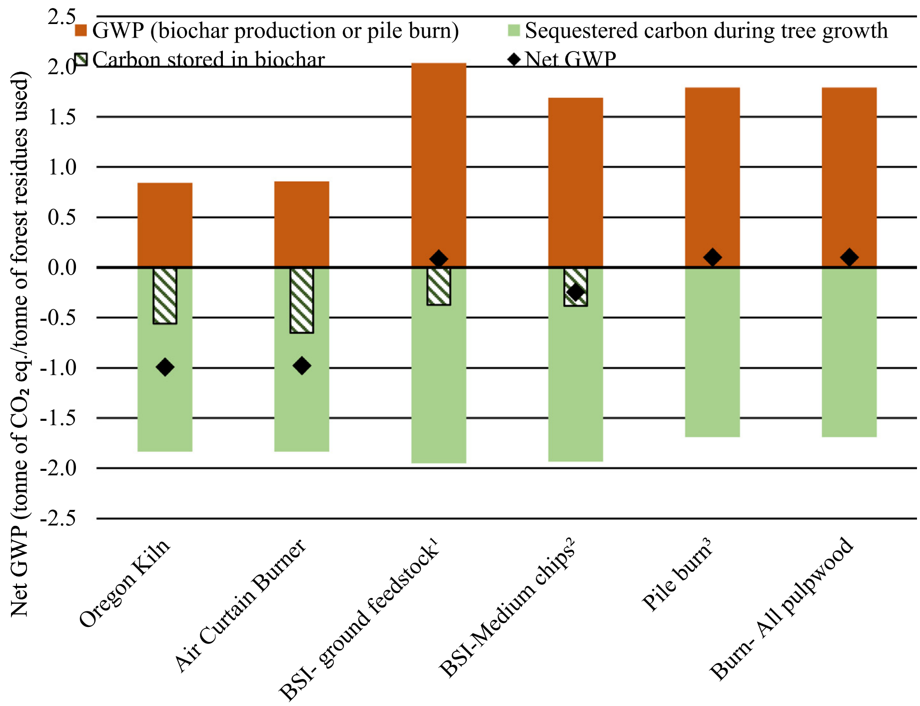

Fig. 10. Net carbon impacts for biochar production at remote biochar production sites compared to burning slash piles.
[1](1/3rd tops + 2/3rd pulpwood) feedstock used in BSI system with power pallet; [2]Pulpwood chips used in BSI system with power pallet); [3](1/3rd tops + 2/3rd pulpwood) pile burned.

4. Discussion

The current study has provided critical information to stakeholders and policymakers to gain a better understanding of the use of forest residues to produce biochar using different portable systems. Challenges that remain is the understanding of the volume of forest residues that are potentially available as feedstocks for bio-based products (Oneil et al., 2017). This in turn is significantly influenced by the current recovery options that are available and the economic value of these options. Aggregating across the entire region provides an estimate of ten million bone dry metric tons (10 MM oven-dry metric tons) per year of potentially available biomass (Table 7).

However, most of the potentially available biomass is not recoverable as it is too far from existing and potential 'in town' processing facilities. In order to access all the potentially available biomass, new alternatives will be required. The option of developing a network of remote biomass conversion sites to densify and aggregate material for eventual transport to markets or energy plants may well be necessary to meet the goals of the Billion-Ton Update (Langholtz et al., 2016).

The comparative analysis of biochar production relative to open burning provides one 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. Those benefits can be measured by avoided emissions from open burning. If efforts are conducted at 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 (Sifford et al., 2016) as well as impacting wildfire behavior. Economic analysis (Sahoo et al., 2018) shows there are still many challenges to overcome, but if we truly want to embark on the vision as embraced by the Billion-Ton Update (Langholtz et al., 2016), more work on portable biomass conversion system is a step in the right direction. The potential for the production of biochar using portable systems appears beneficial to the environment by directly reducing emissions contributing to the GWP compared with pile burn. The BSI system (with medium chips) reduced the net GWP by over 1600 percent over the pile and burn operations. The biochar stored around 0.38 tonnes of CO_2eq out of 1.93 for a tonne of CO_2eq captured in the feedstock during tree growth. Carbon emissions (including biogenic carbon) for biochar production were 1.69 CO_2eq yielding a net GWP emission of -0.25 CO_2eq versus pile and burn of $+0.10$ CO_2eq. Opportunities could be established to support a sustainable bioproduct industry in the United States, to offset carbon emissions, if forest thinning will be adopted to mitigate wildfire and produce biochar from these forest residue.

The assumptions of carbon neutrality from burning forest

Table 7
Total harvested acres and volumes for Washington, Oregon, and California.

	Harvest Acres	Saw timber MMBF[a]	Roadside mt[b] Pulp	Roadside mts[b] Tops	Roadside Tons [b] Branches	Roadside mt[b] Total	Tons[b]/Acre
5 Year Total	1,507,621	32,225	19,187,073	2,295,345	28,544,372	50,026,790	33.2
Annual	301,524	6445	3,837,415	459,069	5,708,874	10,005,358	33.2

[a] MMBF = million board feet.
[b] mt = Metric tons (t).

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biomass had been debated especially when the forest is harvested for bioenergy/fuel production (Zanchi et al., 2012) and the conflicting results were due to methodological assumptions (Bentsen, 2017). The debate is mostly for harvesting forest (especially unsustainable harvesting of the forest leads to deforestation and environmentally sensitive forest region, etc.) for the production of bioenergy and fuel. Forest residues left in the forest decompose slowly and all carbon released to the atmosphere along with other potent GHG emissions such as methane and nitrous oxide based on climate and residues management practices. Burning forest residues onsite/offsite or making bioenergy/fuel suddenly release all carbon along with other potent GHG emissions. In biochar making process (i.e., pyrolysis), a part of the carbon in the biomass develops a calcitrant character which remains inactive to weathering for decades or hundreds of years – carbon sequestration. Moreover, biochar has many environmental benefits including increased soil productivity, soil water holding capacity, nutrient holding capacity, etc. However, the high logistics cost of biomass is one of the major hurdles for the utilization of forest residues and portable systems to make biochar can be the most efficient option for the economical utilization of forest residues.

5. Limitations, sensitivity, and uncertainty

This LCA was created using collected data for biochar production. Some assumptions were made for the various biochar production systems. Details of these assumptions can be found in the main report (Puettmann et al., 2017).

This LCA does not report all the environmental impacts due to the manufacturing of the product, but rather reports the environmental impacts for those categories with established LCA-based methods to track and report. Unreported environmental impacts include (but are not limited to) factors attributable to human health, land-use change, and habitat destruction. In order to assess the local impacts of product manufacturing, additional analysis is required.

Some degree of uncertainty is present in the results due to the variation amongst different data providers. Haul distance of residues to in-town locations proved to show that an increase of 2 h in distance resulted in a 29, 13, and 43 percent increase in GWP for electricity, diesel, and powerplant energy use. When hauling residues 2 h versus processing at a remote location GWP was increased by 8 and 34 percent for diesel and power pallet use, respectively.

6. Conclusions

In this study a cradle-to-gate life cycle assessment approach used to estimate the environmental impacts of producing biochar from forest residues using three portable systems (BSI, Oregon Kiln and Air-Curtain Burner) considering different production sites – processing locations either near a forest or an in-town location (either 2 or 4 h of transport distance for feedstocks)]–, quality of feedstocks (chipped pulp-quality forest residues and ground forest residues), and different sources of power (grid connection for in-town locations and diesel or gasifier-based generator for near-forest locations).

Overall, the production of biochar from forest residues reduced GHG emissions (−0.3 to −1.83 tonnes of CO_2eq./dry tonne of forest residues) compared to pile burn. Among all three portable biochar production systems, both Air-Curtain Burner and Oregon Kiln have higher potential to mitigate GHG emissions compared with the BSI system that used comminuted biomass for the operations and dedicated feedstocks logistics. The Oregon Kiln system 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 as those undertaken by small woodland owners clearing for fuel reduction or restoration projects. The GHG reduction in making biochar at the near-forest location is higher than in-town sites due to requirement feedstock transportation from forest to in-town sites. 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 lowered carbon emissions over the use of a diesel generator at the remote and in-town sites. 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. Feedstock variability has a large impact on both biochar quality and biochar production efficiency. Moisture, contamination such as dirt, and ash content all reduce both quality and efficiency of the biochar. Using these biochar systems for “disposal” of forest residues reduces fuel stocks in forests. It is important to note that each of these biochar production systems also produces a fire risk. Extreme care must be taken to operate these portable systems during safe burning windows, as well as where best to place them. The in-town, options could possibly offer less risk.

In summary, the potential for the production of biochar using portable systems appears beneficial to the environment by reducing GHG emissions compared with pile burn. The current study has provided critical information to all stakeholders and policymakers for a better understanding of the use of forest residues to produce biochar using different portable systems. Opportunities exist to establish a sustainable bioproduct industry in the United States, if forest thinning will be adopted to mitigate wildfire and produce biochar from forest residues.

Authors contribution

Maureen Puettmann: Conceived and designed the analysis, Collected the data, Contributed data or analysis tools, Performed the analysis, Wrote the paper. *Kamalakanta Sahoo:* Conceived and designed the analysis, Contributed data or analysis tools, Performed the analysis, Wrote the paper. *Kelpie Wilson:* Collected the data, Contributed data or analysis tools, Wrote the paper. *Elaine Oneil:* Conceived and designed the analysis, Performed the analysis, Wrote the paper.

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