



Life-cycle assessment and techno-economic analysis of biochar produced from forest residues using portable systems

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Abstract

Purpose Producing biochar from forest residues can help resolve environmental issues by reducing forest fires and mitigating climate change. However, transportation and storage of biomass to a centralized facility are often cost-prohibitive and a major hurdle for the economic feasibility of producing biobased products, including biochar. The purpose of this study was to evaluate the environmental impacts and economic feasibility of manufacturing biochar from forest residues with small-scale portable production systems.

Methods This study evaluated the environmental performance and economic feasibility of biochar produced through three portable systems (biochar solutions incorporated (BSI), Oregon Kiln (OK), and air curtain burner (ACB)) using forest residues in the United States (US). Cradle-to-grave life-cycle assessment (LCA) and techno-economic analysis (TEA) were used to quantify environmental impacts and minimal selling price (MSP) of biochar respectively considering different power sources, production sites, and feedstock qualities.

Results and discussions The results illustrated that the global warming (GW) impact of biochar production through BSI, OK, and ACB was 0.25–1.0, 0.55, and 0.61-t CO₂eq/t biochar applied to the field, respectively. Considering carbon-sequestration, 1-t of biochar produced with the portable system at a near-forest site and applied to the field reduced the GW impact by 0.89–2.6 t CO₂eq. For biochar production, the environmental performance of the BSI system improved substantially (60–70%) when it was powered by a gasifier-based generator instead of a diesel generator. Similarly, near-forest(off-grid) biochar production operations performed better environmentally than the operations at in-town sites due to the reduction in the forest residues transportation emissions. Overall, the net GW impact of biochar produced from forest residues can reduce environmental impacts (i.e., 1–10 times lower CO₂eq emissions) compared with slash-pile burning. The MSP per tonne of biochar produced through BSI, OK, and ACB was \$3,000–\$5,000, \$1,600, and \$580 respectively considering 100 working days per year. However, with improved BSI systems when allowed to operate throughout the year, the MSP can be reduced to below \$1000/t of biochar. Furthermore, considering current government grants and subsidies (i.e., \$12,600/ha for making biochar production from forest residues), the MSP of biochar can be reduced substantially (30–387%) depending on the type of portable system used.

Conclusion The portable small-scale production systems could be environmentally beneficial and economically feasible options to make biochar from forest residues at competitive prices given current government incentives in the US where excess forest biomass and forest residues left in the forest increase the risk of forest fires.

Keywords Life-cycle assessment · Global warming · Techno-economic analysis · Portable production systems · Biochar · Forest residues

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1 Introduction

Forest fires are getting extreme and recurrent in the US as well as globally, because of increased fuel loads (i.e., woody biomass) in the forest and longer dry climatic conditions (Cook and Becker 2017; Sahoo et al. 2019). On the other hand, fire suppression activities have resulted in increased fuel loads (i.e., overstocked stands with small-diameter trees) that are vulnerable to extreme wildfire (Noss et al. 2006).

The forest fires in the US cost lives and huge economic losses (e.g., \$1.84 billion in 2015 as fire suppression cost excluding property damage (Cook and Becker 2017) and \$76–\$130 billion/year from 2008 to 2012 due to adverse health impacts (Fann et al. 2018)). Moreover, for improved wildfire management, it is quite costly (Sahoo et al. 2018) to remove excess woody biomass from the forest especially wildland-urban interface (Stein et al. 2013).

Soil quality degradation and agricultural productivity decline due to a reduction of soil organic matter (SOM) and nutrient imbalances are major constraints in agricultural soils (Agegnehu et al. 2017) that lead to loss of income and productive lands—an existential threat to the global food demands to feed 10 billion people by 2050.

Forest residues or wood waste generated during usual commercial logging operations also present a forest-fire risk that must be removed or treated properly (Page-Dumroese et al. 2017). Moreover, air pollution and other adverse human health impacts are caused due to controlled burning forest residues (Berrill and Han 2017). However, these forest residues are potentially available to produce valuable bio-based products, including bioenergy and biochar.

Biochar production from forest residues can act as a multi-edged approach to mitigate global threats such as forest fires by reducing excess biomass in the forest and climate change; by capturing and storing carbon in soil through agriculture application, while simultaneously improving crop productivity; by enhancing soil quality, allowing lower fertilizer application and irrigation (Qambrani et al. 2017). Note that the decline in agricultural productivity is an existential threat to global food demands to feed 10 billion people by 2050 (Agegnehu et al. 2017).

The main economic obstacle to the use of forest residues distributed across a large geographic region is their high logistical collection and aggregation costs (Sahoo et al. 2019; Wright et al. 2008; Yazan et al. 2016; Mirkouei et al. 2017). Furthermore, due to low bulk and energy density, and high moisture content (MC), biomass collection, transport, and handling costs are high (Parkhurst et al. 2016; Sahoo, 2017; Sahoo et al. 2018). The Waste to Wisdom (WTW) research project (WTW 2018), with a focus on the Pacific Northwest of the US, was initiated to identify technologies and processes that could utilize these residues for economically valuable bio-based products that could offset the costs of fuel reduction

treatments and forest restoration that may provide employment opportunities in rural areas (Sahoo et al. 2018).

Large-scale biochar production system—using slow pyrolysis at a 450–500 °C temperature range (Carrasco et al. 2017)—may not be financially feasible due to the high biomass logistics cost of transporting low-value forest residues to industrial facilities (Kuppens et al. 2014; Wrobel-Tobiszewska et al. 2015). Therefore, portable platforms have been proposed (Berry and Sessions 2018; Sahoo et al. 2019) that can perform biomass conversion and produce various biomass-based products close to the supply (i.e., near-forest). These studies (Badger et al. 2010; Berry and Sessions 2018; Brown and Brady 2012; Sahoo et al. 2019) primarily focused on the techno-economics of biochar production and better supply chain configuration. However, the life-cycle assessment (LCA) and techno-economic analysis (TEA) of biochar production with a portable system can illustrate both the bottom line environmental impacts and economic feasibility, which can be valuable to the various stakeholders including forest owners, biochar producers, carbon market, policymakers, and society.

Alhashimi and Aktas (2017) discuss various studies on LCA biochar production. These studies are based on centralized large-scale production plants that utilize agricultural residues (Dutta and Raghavan 2014; Roberts et al. 2010) or mixed types (Hammond et al. 2011) of feedstocks and considering biochar as co-products rather than main products (Hammond et al. 2011; Lu and El Hanandeh 2019). Roberts et al. (2010) studied the biochar-pyrolysis system, which compared the life-cycle impacts of biochar produced from crop residues (i.e., corn stover), woody biomass (i.e., yard waste), and energy crop (i.e., switchgrass) feedstocks. Clare et al. (2015) compared the carbon storage potential and economic feasibility of biochar production with that of bioenergy production. Field et al. (2013) have studied the biochar production from various feedstocks considering various technologies (i.e., slow and fast pyrolysis), and applications including use as energy, a soil amendment that can mitigate up to 1.4-t CO₂eq/t of biomass. The net carbon abatement potential of biochar depends on the biochar production system boundary, feedstocks, products, technologies, and application scenarios. Lee et al. (2010) found that biochar and energy production produced less GHG emissions compared with others such as in-situ decompositions, composting, combustion for heat and energy, or conversion to liquid biofuel.

Portable small-scale systems can be economically viable alternatives. However, studies on portable and small-scale biochar production systems are few and not extensive. There are some studies on portable pyrolysis systems capable of producing biochar, though most of these systems were optimized to produce bio-oil, not biochar as the primary product (Badger et al. 2010; Chen et al. 2018; Mirkouei et al. 2016; Polagye et al. 2007) with the bio-oil then transported to a

central facility to produce transportation fuels. Rosas et al. (2015) mentioned that there is a significant reduction in GHG emissions related to feedstock transportation compared with a centralized system and thus lower net global warming impact of biochar produced from vineyard residues. Bergman et al. (2019), Gu and Bergman (2016), and Gu et al. (2018) performed a cradle-to-gate LCA on an advanced woody biomass thermochemical conversion unit producing synthesis gas (syngas) for electricity generation and biochar for activated carbon. Biochar, in this case, significantly reduced the global warming impact for syngas electricity compared with fossil resource-based electricity generation (Gu and Bergman 2017). The carbon stored in biochar was attributed to carbon sequestration value only, without considering the downstream indirect effects of applying biochar in soil. Bergman et al. (2016) showed that biochar pellets broadcast in the field had relatively small contributions to climate change relative to the carbon sequestration potential of the biochar pellets. Several biochar LCA studies followed a similar approach, essentially considering biochar as a GHG offset product to the climate change impact of a bioenergy production platform (Homagain et al. 2015; Hudiburg et al. 2011; Ramachandran et al. 2017). Many biochar LCA studies have looked beyond the direct carbon sequestration/storage values of biochar including avoided soil GHG emissions, reduced fertilizer use in crop production (Muñoz et al. 2017; Pereira et al. 2016), increased agronomic yield, and transportation distance and logistics sensitivities for applying biochar closer to where it is produced (Peters et al. 2015; Rosas et al. 2015; Wang et al. 2014). Transportation distances are often important input parameters for feedstock and biochar logistics, and biochar application phases.

The application of biochar is diverse including land reclamation (both for agriculture and forest), horticulture, wastewater treatment, animal feed, and cosmetics (Li et al. 2020; Qambrani et al. 2017). The application of biochar for land reclamation is most widely studied (Li et al. 2020) and is the most important application that will drive biochar demand in the future (Sasatani and Eastin 2018). The overall environmental impacts of biochar applied to the soil ultimately depend on the carbon storage potential of biochar which decreases with time due to the mineralization process. Mineralization of biochar carbon in the soil is complex and is affected by multiple parameters including feedstocks, pyrolysis temperature, biochar properties, and soil environment (Gurwick et al. 2013; Singh et al. 2012; Wang et al. 2016). Biochar contains both labile and recalcitrant carbon where the former is prone to accelerated mineralization compared with the later one (Wang et al. 2016). Carbon storage or biochar stability is estimated using multiple parameters (Leng et al. 2019) such as half-life, mean resident time (MRT), carbon stability factor (CSF) (Wang et al. 2014), and BC_{+100} (the percentage of organic C in biochar that remains stable in soil for more than 100 years) which vary widely. For example, a

review study on MRT (a reciprocal of the decomposition rate) on biochar showed that biochar can remain in the soil between 8 and 4000 years (Gurwick et al. 2013), and MRT mainly dependent on biochar properties especially the content of recalcitrant carbon in the biochar. Carbon in biochar produced especially from woody feedstocks at higher pyrolysis temperature is mostly contained recalcitrant carbon (> 97%) (Singh et al. 2012; Wang et al. 2016). The MRT for recalcitrant carbon in biochar is far more than 100 years (Singh et al. 2012; Wang et al. 2016), the standard timeframe for performing LCA and estimating biochar's carbon sequestration potential. International Biochar Initiative performed a meta-analysis and estimated the fraction of biochar-carbon remain stable or sequestered in the soil after 100 years (BC_{+100}) considering the H/C_{org} ratio of biochar (i.e., biochar with H/C_{org} of 0.4 has BC_{+100} value of 80.5) (Budai et al. 2013). The H/C_{org} ratio of biochar depends on the type of biomass and woody feedstocks have lower H/C_{org} ratio especially at higher pyrolysis temperature and longer residence time (Ronsse et al. 2013).

Overall, there are some key aspects of biochar production in portable systems that have not been considered in previous studies. Forest residues quality, measured by variables such as type of biomass and its MC, size, and ash content, has a substantial influence on the biochar quality (Inoue et al. 2011), biochar yield, and the productivity of biochar manufacturing systems. The types of portable production systems and their locations also influence the overall biochar production performance. For example, the BSI (manufactured by biochar solutions incorporated) system requires electrical power to operate where it may not be a feasible option to get grid connection such as a near-forest biochar production site (Sahoo et al. 2019; SERC 2016). The usual option is to use a diesel generator to power the BSI system at the near-forest site operation, which can have large negative environmental impacts due to the use of fossil fuel. However, a wood gasifier-based generator is an alternative with a low environmental footprint option compared with a diesel generator that could power a BSI system (WTW 2018; Sahoo et al. 2019; Alanya-Rosenbaum and Bergman 2019; Alanya-Rosenbaum et al. 2018). Other portable systems that can be alternatives to the BSI system, like the Oregon Kiln (OK) and air curtain burner (ACB), have been tested by Puettmann et al. (2020) and Wilson (2017). The OK and ACB can process much larger-size forest residues, do not require comminution of forest residues, and do not require electrical power for operation. Recently, Puettmann et al. (2020) analyzed the lifecycle impacts of producing biochar with BSI, OK, and ACB. However, this study is a cradle to gate LCA study. Biochar is very bulky (or low bulk density) and its transportation and application in the field may incur additional environmental impacts and cost and may influence the overall biochar performance. Therefore, a cradle-to-grave comparative LCA

study of biochar production from forest residues for these three portable systems (BSI, OK, and ACB) considering various feedstock qualities and production site locations (near-forest and in-town), and field application can provide critical information to stakeholders and policymakers to make decisions for the best usage of forest residues and the associated portable system best-suited to varying conditions.

In this study, an integrated cradle-to-grave LCA and TEA was conducted to measure the environmental performance and economic feasibility of making biochar, the final product from forest residues in the western US using three portable systems, namely BSI, OK, and ACB that have been developed, tested, and marketed in the US. The environmental impacts were estimated using a cradle-to-grave LCA approach (ISO 2006a, b). A discounted cash flow rate of return (DCFROR) model (Sahoo et al. 2019) was used to estimate the financial performance and the economic feasibility of producing biochar.

The following describes the various scenarios analyzed in this study. The BSI system was studied considering biochar production in different locations (near-forest (maximum 1-h travel time from feedstocks) and in-town (maximum 2–4 h travel time from feedstocks), feedstock qualities (chipped and ground forest residues with variable moisture and ash content), and different power sources (in-town locations used available grids and near-forest locations used diesel or wood gasifier-based generator)). The BSI system was tested extensively by the Schatz Energy Research Center where performance data were collected and analyzed (Severy et al. 2016; Severy et al. 2018). The OK and ACB were tested at in-forest locations (just near the forest residues piles) (Wilson 2017). The TEA included all costs incurred from feedstocks preparation, logistics, biochar production, product transportation, and field application. The results were presented as various environmental impacts (especially global warming (GW) impact), economic feasibility (especially minimum selling price (MSP)) per unit mass of biochar produced, and sensitivity analyses.

2 Methods

This study investigated the environmental impacts and economic feasibility of producing biochar using portable platforms (biochar solutions incorporated (BSI), Oregon Kiln (OK), and air curtain burner (ACB) (Fig. 1)) from forest residues either at the near-forest setup or in-town locations (only for BSI) in the western US.

A cradle-to-grave LCA approach was used to estimate the environmental impacts of biochar produced from forest residues and applied to the soil. The DCFROR model was developed to estimate financial performances, especially the minimum selling price (MSP) of biochar delivered to users. The primary data used in this study were compiled from the

Waste to Wisdom (WTW) research project (WTW 2018), where experiments were conducted for forest residues harvesting, feedstocks preparation, and then link to primary data collected from the portable biochar production systems. There were several scenarios studied considering types of feedstock, production system, processing location, and sources of electricity used in operating the production systems (Fig. 2). BSI portable systems can produce biochar from forest residues either (a) at a remote site very close to the forest, i.e., near-forest sites or (b) in-town sites that are located either 2 or 4 h of travel time away from the forest (Puettmann et al. 2020). In the latter case (b), forest residues are transported in trucks to the in-town sites. However, OK and ACB can produce biochar at the parcel, a small piece of land right at source without forest residues transportation and minimal or no comminution.

2.1 Life-cycle assessment

This study conducted the lifecycle assessment by following the ISO 14040 and ISO 14044 standards (ISO 2006a, b). Using primary and secondary data provided, life-cycle inventory (LCI) was developed for biochar in each scenario and SimaPro 8.5 life-cycle assessment (LCA) modeling software estimated the associated life-cycle impact categories including global warming (PRe Consultants 2019). This study deals with only a single product, i.e., biochar from forest residues and no co-product exists, but whenever there is a need for attributing life-cycle inventory and impacts among various co-products, we have used a mass allocation approach.

2.1.1 Goal and scope

The scope of the LCA study was to quantify the environmental footprints of biochar produced from forest residues using portable systems through a cradle-to-grave approach. The biochar supply chain covered upstream unit processes (residues harvesting and collection, feedstock processing, and biomass transportation/hauling), and the main biochar production process, biochar transport, and field application (i.e., biochar spread into the soil). Forest residues were considered waste generated during the sawlog harvesting operation. Therefore, forestry operations related to the management of forest and harvesting of trees were excluded from this LCA (Puettmann et al. 2017a).

Whether comminution or break down of forest residues occurred depended on the selected biochar system. BSI biochar production unit used forest residues that were either chipped or ground. The other two portable systems—OK and ACB—used uncomminuted forest residues that required length reduction only using a chainsaw (manually-operated). The biochar quality produced from these portable systems partially depended on feedstock type and their properties.

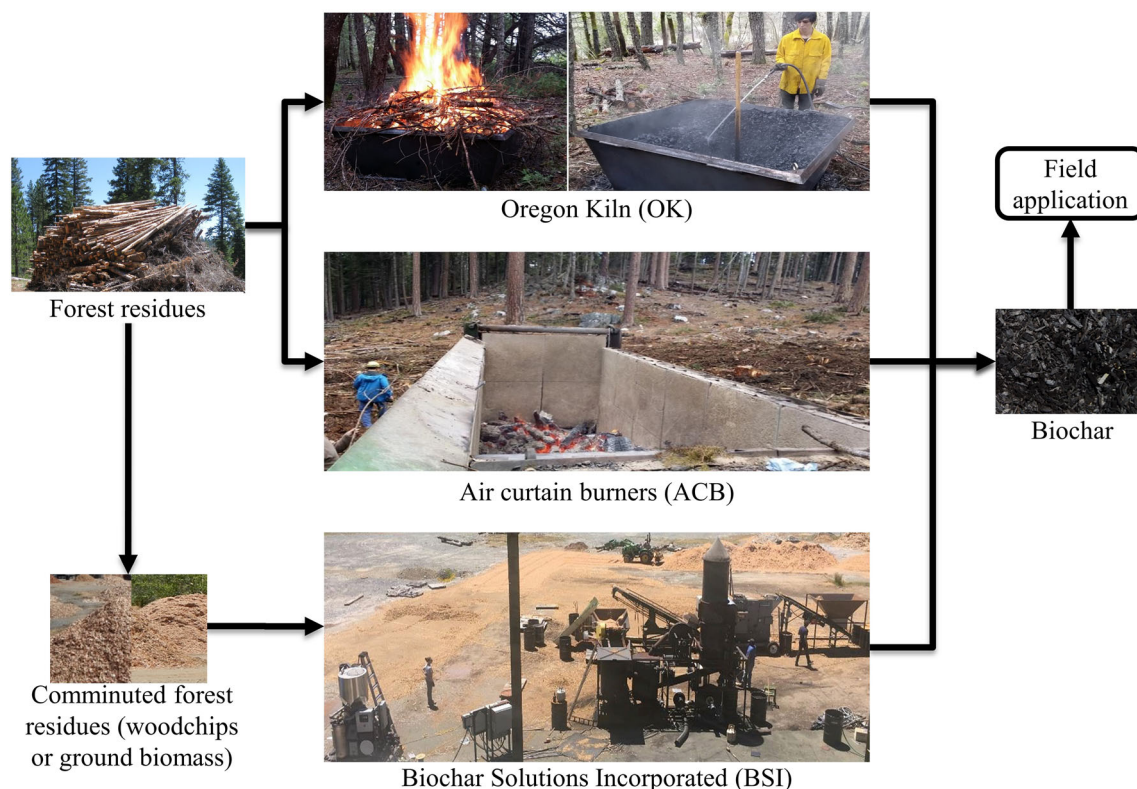


Fig. 1 Biochar production with portable processing systems

The use of electrical power depended on the selected biochar system. The operation of the BSI biochar production system requires power that was supplied from either the Power Pallet-PP20 (woody) biomass gasifier (All Power Labs, Berkeley, California, USA), diesel generator, or grid if

available. The grid-based electricity is usually unavailable for near-forest locations but an in-town facility can have a grid connection for operating these portable systems.

The functional unit in this LCA study was considered 1 t of biochar sold to a consumer with biochar applied in the field. A

Fig. 2 Biochar production scenarios considering feedstock types, production systems, processing locations, and power sources

Feedstock	Production system	Production location	Source of electricity	Studied scenarios ^b in this study
F1- Ground conifer and no contamination F2- Ground conifer and 9% contamination F3- Ground conifer and 2/3 bole, 1/3 tops ^a F4-Chipped (small) conifer and no contamination F5-Chipped (medium) conifer and no contamination	P1- BSI P2- Oregon kiln P3- Air curtain burner	L1- Near forest L2- In-town, 2-hr transport distance L3- In-town, 4-hr transport distance	E1- Diesel generator E2- Woody gasifier-based generator E3- Grid	For BSI S1: F1P1L1E1 S2: F1P1L1E2 S3: F2P1L1E1 S4: F2P1L1E2 S5: F3P1L1E1 S6: F3P1L1E2 S7: F4P1L1E1 S8: F4P1L1E2 S9: F5P1L1E1 S10: F5P1L1E2 S11: F1P1L2E1 S12: F1P1L3E1 S13: F1P1L2E2 S14: F1P1L3E2 For Oregon kiln and Air curtain burner S15: F1P1L2E3 S16: F1P1L3E3 S17: F3P1L2E1 S18: F3P1L3E1 S19: F3P1L2E2 S20: F3P1L3E2 S21: F3P1L2E3 S22: F3P1L3E3 S23: F3P2L1 S24: F3P3L1

^aChipped (2/3 bole, 1/3 tops) biomass was processed for BSI system. But uncomminuted biomass was processed in Oregon kiln and air curtain burner

^bA scenario (S) is a combination of Feedstock type (F), Production system (P), Location of biochar processing (L), and sources of Electricity to operate the system (E)

second functional unit (i.e., percent of fixed carbon in the biochar) was used to compare different feedstock inputs and biochar systems. A third functional unit (i.e., one metric tonne of forest residue (oven-dry basis)) was used for comparison of slash pile burning and the use of forest residues to make biochar. The primary data on the biochar production operations including feedstocks inputs, electricity and fuel consumption, ancillary materials inputs, and biochar outputs were collected directly from each portable system. Where data were lacking, assumptions were made based on published reports or by speaking to experts. Forest residues harvesting, collection, transportation, and comminution data were obtained from (Oneil et al. 2017; Sahoo et al. 2018). Biochar production data were provided by Schatz Energy Research Center, Humboldt State University (SERC 2016) for the BSI unit, and by Wilson Biochar Associates (Wilson 2017) for the OK and ACB (Puettmann et al. 2018).

2.1.2 System boundaries and description of biochar production systems

The system boundary starts with forest residues harvesting and ends with biochar applied to the field. Figure 3 shows the system boundary of biochar production using the BSI portable unit. Figure 4 shows the system boundaries for the production of biochar using the OK (Fig. 4a) and ACB (Fig. 4b) developed by Wilson Biochar Associates (Wilson 2017). The detailed description of forest residues logistics was mentioned by Oneil et al. (2017). The detailed description of biochar production with BSI system was provided in (SERC 2016) and (Severy et al. 2018) Biochar production with OK and ACB was provided in Puettmann et al. (2017b)

All three systems exclude forest logging operations that included tree felling and yarding loading but include hauling of forest residues to the biochar system (Oneil et al. 2017). For the BSI system, forest residues were processed and sorted into pulp logs, branches, and tops. Pulp logs provided very high-quality biomass, hence, were transported to the processing site, for chipping and screening before use in the BSI system to produce biochar. Pulp logs were available in the US Pacific Northwest because of the loss of pulp and paper mills in this region but may have limited availability outside this region. Compared with pulpwood, branches and tops are lower in quality and thus are processed using horizontal grinders and hauled to the processing site. Before entering the BSI system to make biochar, all comminuted woody biomass was screened. For the BSI system, a detailed technical description to produce biochar is described by Severy et al. (2016) and Severy et al. (2018). About 20 kW of electricity is required to run the BSI system and three power source types were considered in this study based on the actual near forest or in-town biochar production sites (Sahoo et al. 2019). For the OKs, they are lightweight (less than 100 kg) and portable,

allowing several kilns to be located on the forest roads with transportation of residues to the roadside from the forest. OKs can handle larger-size forest residues (< 15 cm diameter) and thus do not require comminution of the biomass, but may require some minimal preprocessing. Forest residues were sorted and hauled to the processing site, where the boles/branches/tops were further processed into smaller lengths using a chain saw. For the ACB, in contrast, they can handle larger length (length of forest residues should be smaller than the length of ACB (i.e., 9.2 m) but no limit in stem diameter) biomass so does not require any preprocessing. This unit was used to process mostly freshly-cut (green) slash.

Although the purpose of using an ACB unit is slash disposal through incineration, the units do produce large batches of biochar. ACB was bigger compared with OK but operated similarly as OK. However, the operating temperature of ACB was higher than OK and thus produced biochar that has a higher fixed carbon percentage. The ACB does have a 36-kW engine to operate a blower but was not used in this study, whereas an OK does not require any power source for its operation.

2.1.3 Forest residues harvesting, logistics, and preparation of feedstocks

This study considered forest residues harvested from timberland during commercial logging operations in the five regions (Oneil et al. 2017) of the US Pacific Northwest. All five harvesting sites produced about 82 ODMT (oven-dry metric tonnes) woody biomass/ha. Forest residue harvesting including collection and processing from conifer forests served as an input into the biochar production systems. One source, pulpwood, was hauled to the conversion site (near-forest or in-town) as whole logs using trucks. The other source, logging residue (tops and branches), was ground at the forest landing, hoisted into a dump truck, and hauled to the near-forest site. For the near-forest processing site, haul time is limited to a maximum of 1 h from the log harvest sites. For the biochar production at the in-town processing site, the biomass hauling time is limited to 2 or 4 h from harvesting sites. At each biochar processing site (near-forest or in-town), the pulp logs were chipped using a medium chipper or a micro chipper and screened before feeding to the BSI unit, but tops and branches were ground (~ 12 mm) with grinders at the forest landing and transported to the biochar processing site, stored, and screened before loaded into the BSI unit.

The BSI biochar system processed feedstocks are mentioned in Table 1. However, the feedstocks with higher ash (i.e., > 15%) and moisture (i.e., > 25% wb) became more difficult to process and produced lower quality (i.e., lower percent of fixed carbon) 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; Severy et al. 2018). Higher amounts of fixed carbon in the biochar give both a higher value energy product and a better soil amendment with greater carbon sequestration potential. In the original WTW design, the heat generated in the process of biochar production was wasted. In the later stage of the WTW project, the BSI system was redesigned to utilize waste heat that improved the throughput and biochar yield. A dryer unit was added for handling higher MC feedstocks. In addition, a dual-auger replaced a single-auger unit increased biochar production capacity [both throughput (21%) and biochar yield (45%) increase compared with the single-auger BSI] (Severy et al. 2018).

Logistics operations to produce feedstocks for OK and ACB systems are shown in Fig. 4. It was assumed that forest residues were collected, separated into smaller diameter (< 15 cm) branches and tops, and piled in the forest during harvesting of sawlogs. OKs were set up in the forest and skid loaders were used to bring sorted forest residues near the kiln and forest residues were cut to a maximum 1.2-meter length using chain saws. The logistics operations for the ACB were similar to the OK, except no size reduction of the branches and tops (Fig. 4b). The size of the ACB was large enough to consume forest residues without any size-reduction. A loader was used to feed forest residues periodically into the ACB.

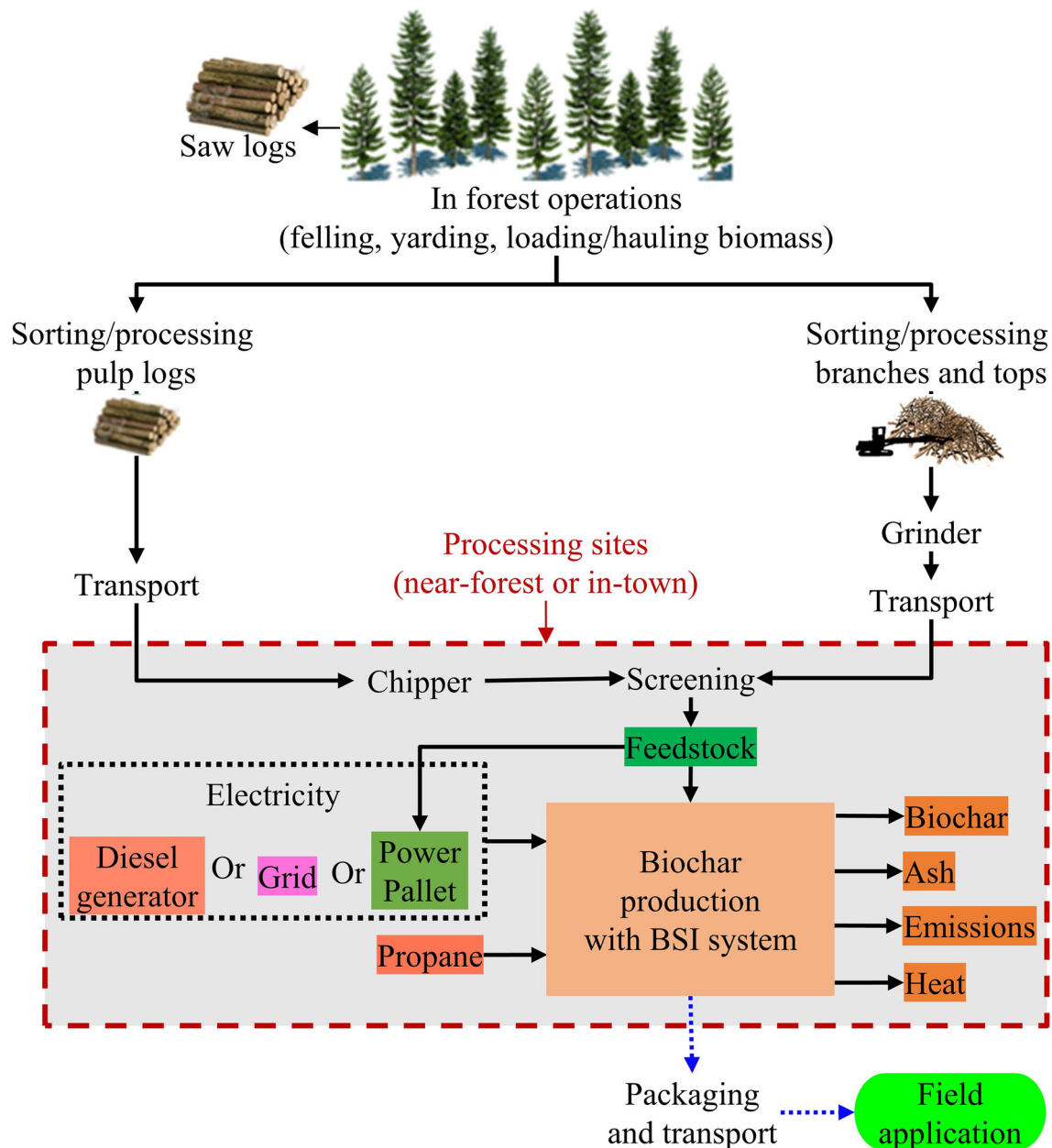


Fig. 3 Biochar production using the BSI system at either a near-forest or in-town biomass conversion site location (Puettmann et al. 2020)

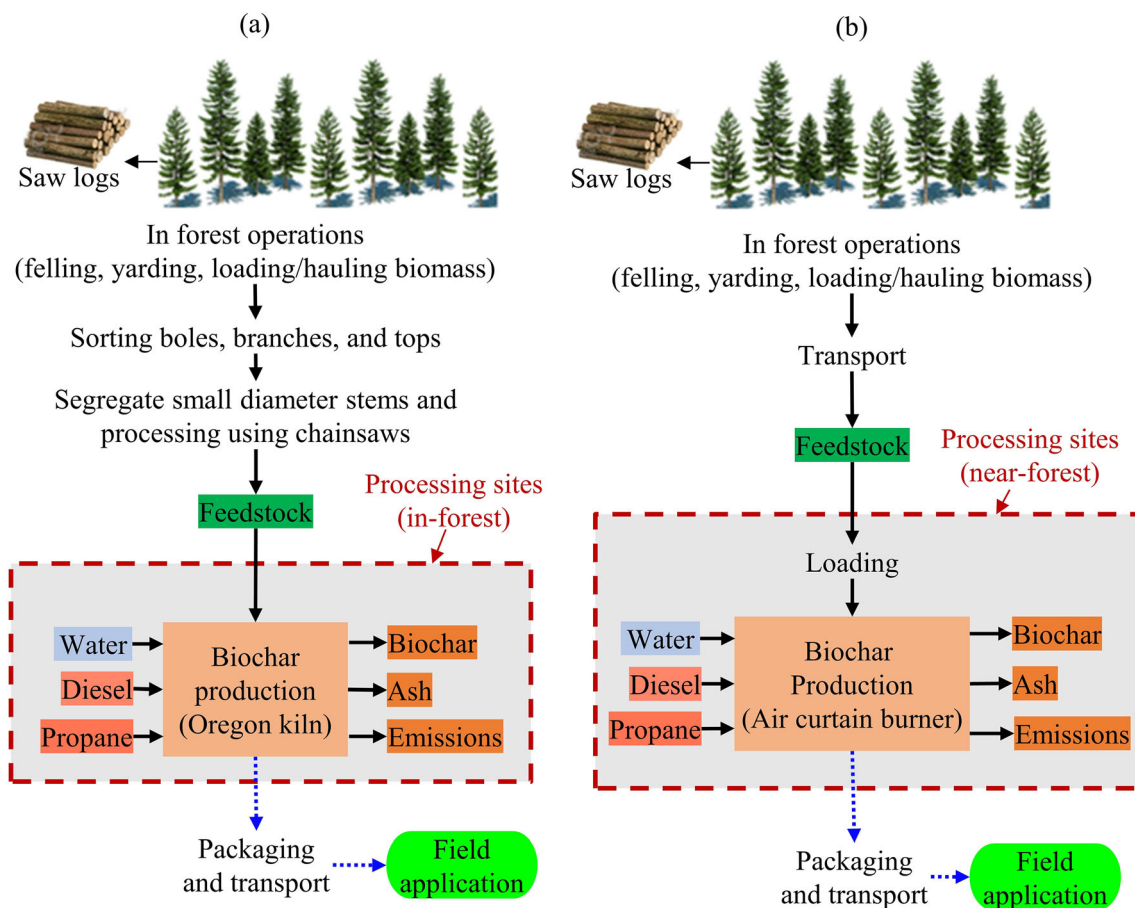


Fig. 4 Biomass logistics and biochar processing through **a** OK and **b** ACB (Puettmann et al. 2020)

2.1.4 Biochar production systems

Biochar systems incorporated This study considered the production of biochar at the near-forest and in-town locations with the biochar systems incorporated (BSI) system which is a down-draft gasifier. The detailed description and operation of the BSI machine are presented in the supporting document (section 2.1, Fig. A1). It is rated to process 0.32 dry tonne/h of woody biomass corresponding to 0.043 t/h of biochar (SERC 2016). However, with the improved system (a dual-auger type), the throughput was increased to 0.38 dry t/h (Severy

et al. 2018) with the same production ratio. Due to no or rare grid connectivity for the near-forest locations, either a diesel generator or woody gasifier-based generator (i.e., Power Pallet) was used to operate the BSI system. However, it was assumed that in-town locations were well connected with grid electricity and biochar production had options to use electricity either from the grid, a diesel generator, or a gasifier-based generator. As the cost and environmental impacts of all three electricity sources are different, therefore this study compared the performances of biochar productions considering different sources of electricity.

Table 1 Characteristics of woody feedstocks used in the BSI system for biochar production (Puettmann et al. 2018)

Feedstock scenarios	Species	Contaminant	Comminution method	Ash content	Moisture content (wet basis)	Moisture content (dry basis)
F1	Conifer	None	Ground	1.68%	16.93%	20.39%
F2	Conifer	9% soil	Ground	11.45%	14.91%	17.53%
F3	Conifer	2/3 bole, 1/3 tops	Ground	3.65%	16.20%	19.33%
F4	Conifer	none	Chip, small	2.13%	20.66%	26.04%
F5	Conifer	none	Chip, medium	0.08%	25.18%	33.65%

Oregon Kiln The Oregon Kiln (OK) (Fig. A2) is a simple pyramidal shape kiln of capacity is 1.1 m^3 (1.5 m^2 top, 1.2 m^2 bottom, and a height of 0.6 m) and fabricated with steel sheet metal of 2 mm thickness. It is an alternative to pile burning of forest residues and optimized for use in in-forest settings. OK pyrolyzes the biomass and uses a cap or curtain of flame to exclude oxygen from the biomass—the principle of flame carbonization. These technologies incur low to extremely low capital cost, operate in batches, and process uncomminuted biomass, i.e., feedstock with no requirement for chipping and transport (Page-Dumroese et al. 2017; Wilson 2017).

The OK was similar to a “Smokeless kiln” which produce well-carbonized biochar. The reported biomass to biochar conversion efficiency was 13 to 20% which depended on the characteristics feedstock used (Inoue et al. 2011). During starting, the fire is kindled in the bottom of the kiln and new wood is added slowly in layers. The flame from each new layer of biomass restricts air to the layer below and thus enables the pyrolysis of biomass. Due to the presence of flame on the top, most of the smoke coming from biomass burns in the flame and produces no or less smoke. Biochar is quenched with water or capped with dirt to prevent air intrusion once the kiln is full of char.

Air curtain burner Air curtain burner (ACB) is large and equipped with refractory-lined boxes, and having powerful blowers to incinerate or burn woody biomass to ash. This study used the S-220 model ACB (9.2 m length, 2.6 m wide, and 2.6 m high) (Fig. A3), which can be considered a scaled-up version of the OK. A 36 kW diesel engine can be used to operate the fan.

An excavator or a loader was used to load the biomass into the ACB. Managing loader is expensive and its overall biomass processing capacity depends on the travel distance to reach the feedstock and sorting requirement of feedstock. If the biomass processing capacity of the ACB is lower than the loader, the former can serve more than one ACB to avoid equipment idle time. To dispose of the forest residues, the ACB is used in incineration mode (i.e., no biochar production) where the diesel-powered blower runs continuously throughout its operation. However, in pyrolysis mode, using dry feedstock, we assume no use of the blower. However, some users with wetter feedstocks might perform better by raising the temperature in the unit and helping dry the feedstock, giving this unit considerable flexibility for processing feedstocks in different conditions. The ACB operated in batches. The ACB unit is unloaded with the help of an excavator and hot char quenched using water. ACB produced biochar with higher fixed carbon, compared with the OK. Table 2 gives the production parameters and assumptions used in the ACB model.

2.1.5 Biochar transport and field application

Biochar produced through portable systems has a low bulk density (Sahoo et al. 2019) and thus expensive for long-distance truck transportation. Anderson et al. (2016) mentioned that biochar was packed in large bags (i.e., super sacks) and loaded into the truck for road transportation. However, packaging incurs cost and the use of plastic sacks can have negative environmental impacts. Therefore, this study assumed bulk truck transport (i.e., chip van) similar to wood chips or sawdust (Sahoo et al. 2018) and does not require the packaging of biochar. Biochar produced from in-forest locations was considered to be applied in the forest or provided to consumers with a maximum distance of 50 km. Similarly, biochar produced from in-town locations was used locally with a maximum delivered transport distance of 50 km. Biochar was assumed to apply in either forest or agricultural lands (Bergman et al. 2016; Page-Dumroese et al. 2016; Shackley et al. 2011). Bergman et al. (2016) provided the details of biochar application in forest soils. A similar setup (or agricultural equipment for solid manure spreading) can be used to apply biochar in the agricultural land (Shackley et al. 2011).

2.1.6 Lifecycle inventory

Life-cycle inventory (LCI) flows are derived from modeling primary (operational) data from a production system's life-cycle. The primary and secondary data for this study were collected from a variety of sources (Table 2). The equipment used for biochar production is reported in Table A1. For a complete understanding of biomass collections systems and machine productivity rates, refer to Oneil et al. (2017). Table A2 provides the total fuel requirements for residue (i.e., 1 t of forest residues) collection and handling, processing (chipped or ground), loading and unloading, and transportation to and from the landing to a designated biochar processing site.

Table 3 shows the various inputs during biochar production through BSI, OK, and ACB. Propane was used during startup fuel for the pyrolysis under all options.

The degree of carbonization and fixed carbon percentage in biochar was typically high for both the OK and ACB, which was due to the high pyrolysis temperature (i.e., ~ 680 to 750 °C (Cornelissen et al. 2016)) and the long residence time of feedstock in the kiln (Cornelissen et al. 2016). Batch processes operate differently than continuous processes. The pyrolysis process in the OK can be characterized as a continuous batch system with fully-carbonized biochar generally produced. The ACB, like the OK, is a batch process but non-continuous, so the unit must be unloaded and quenched at the end of each batch. The BSI system can be considered a continuous process. Each system released emissions back to the environment during its operation both indirectly and directly. Emission data

Table 2 Primary and secondary data types and sources used in this study (Puettmann et al. 2020)

Data type	Data source	Notes
Biochar systems incorporated (BSI)	(SERC 2016)	Experimental study
Air curtain burner (ACB)	Wilson Biochar Associates	(Puettmann et al. 2020)
Oregon Kiln (OK)	Wilson Biochar Associates	(Puettmann et al. 2020)
Residue collection	(Oneil et al. 2017)	
Biochar emission factors	(Severy et al. 2018), (Cornelissen et al. 2016)	
Field application	(Bergman et al. 2016)	Estimates from field experience
End of life of biochar	(Budai et al. 2013; Wang et al. 2016)	
Slash emission factors	(Oneil et al. 2017)	
Propane	LPG, combusted in industrial equipment/RNA	DATASmart (LTS 2019)
electricity grid	Electricity, at eGrid, NWPP, 2008/RNA U	DATASmart (LTS 2019)
Diesel fuel	Diesel, combusted in industrial equipment NREL/US U	DATASmart (LTS 2019)
Gasoline	Gasoline, combusted in equipment NREL/US	DATASmart (LTS 2019)

are critical indicators of a product's environmental performance. For the BSI system, emission results initially obtained from SERC (2016) reported high levels of CO, propane, NO_x, and SO₂. These emissions were likely over the threshold of the sensors caused by problems with maintaining the flow rate of oxygen into the flare (Fig. 3) resulting in incomplete combustion and high levels of CO, propane, NO_x, and SO₂, and low levels of CO₂. SERC concluded that emissions can be mitigated by increasing the size of the flare. Adjustments were made in the flow rate of oxygen along with using a dual-auger system to increase production and efficiencies; a subsequent test in 2016 was made using medium-size wood chips in the BSI machine (Severy et al. 2018). Air emissions from this 2016 test were used in this analysis. The emission factors for this run are reported in Table A3 along with emissions factors for the slash pile burning, the OK, and the ACB. For the second BSI test, CO emissions were lowered due to more complete combustion with CO and unburned hydrocarbons (propane) converted to CO₂. Carbon dioxide and biogenic emissions increased. Slash pile burn emissions were obtained from Oneil et al. (2017) and the OK and ACB 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 2016 test (Severy et al. 2018). The truck transport (i.e., chip van) was considered for bulk transport of biochar from point of production to the application site with a maximum transport distance of 50 km. Biochar is bulky (~ 106 kg/m³ (Sahoo et al. 2019)) and the loading capacity of the truck was estimated to 10.4 tonne that is about half than normal and thus incurs large transportation costs and environmental impacts. Bergman et al. (2016) estimated the LCI of applying biochar into the forest and the main inputs were equipment (82 kW forwarder with a field capacity

of 6.3 t/h) and fuel (3.37-l diesel and 2.2-l gasoline used per tonne of biochar applied in the forest).

2.1.7 Life-cycle impact assessment

LCI flows such air and water emissions from each product are aggregated using a specific life-cycle impact assessment (LCIA) method to estimate the potential environmental impacts, especially GW. The Tools for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) impact category method was selected for this environmental assessment (US-EPA 2012) because it is specifically designed for North America. However, only the GW impact category was presented in this study. Carbon neutrality—biogenic carbon released during biochar production is equal to the CO₂ absorbed from the atmosphere during tree growth—was assumed. In the case of comparisons with pile burn of slash or forest residues, carbon neutrality was not assumed. In this case, production emission was reported as a positive, and negative carbon emission included was carbon uptake during tree growth and carbon content of biochar.

Net greenhouse gas is reported by taking the production emissions and the carbon stored in the biochar after 100 years of applications, i.e., in soil. However, the carbon in the biochar degrades with time, especially the labile carbon component in the biochar, but recalcitrant carbon in the biochar remains in the soil for a very long time (Singh et al. 2012). There are many experimental studies to calculate the life of biochar carbon sequestered in the soil considering feedstocks, biochar production parameters, biochar properties, soil environment, and soil management practices (Leng et al. 2019; Singh et al. 2012; Wang et al. 2016). Moreover, there are several parameters

Table 3 Gate-to-gate lifecycle inventories for the production of 1-t biochar (Puettmann et al. 2020)

	Units	BSI					OK	ACB
		Ground, clean	Ground, 9% soil	Ground, 2/3 bole, 1/3 tops	Chipped, small, clean	Chipped, medium, clean		
Input resources								
Feedstock	kg (dry)	6,937 ^a /6,550 ^{b,c}	7,934 ^a /7,575 ^{b,c}	7,187 ^a /6,781 ^{b,c}	5,361 ^a /5,059 ^{b,c}	8,831 ^a /8,392 ^{b,c}	5,000	28,205
Biochar yield (biochar produced per tonne of forest residues)	%	16	14	16	21	13	20	6.5
Gasifier-based generator's biomass input	kg	387 ^a /0 ^{b,c}	359 ^a /0 ^{b,c}	406 ^a /0 ^{b,c}	302 ^a /0 ^{b,c}	462 ^a /0 ^{b,c}		
Diesel	L	121 ^b /0 ^{a,c}	158 ^b /0 ^{a,c}	110 ^b /0 ^{a,c}	169 ^b /0 ^{a,c}	206 ^b /0 ^{a,c}	90	112
Electricity (from grid)	kWh	0 ^{a,b} /223 ^c	0 ^{a,b} /207 ^c	0 ^{a,b} /234 ^c	0 ^{a,b} /174 ^c	0 ^{a,b} /266 ^c		
Propane	L	3,005	1,037	1,727	4,578	7,760	1,020	441
Water (for quenching)	L	0	0	0	0	0	2,000	2,000
Output products*	Units							
Biochar	kg	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Fixed carbon	%	79	58	65	60	83	76	89

^a Include woodchips consumed in power pallet (gasifier-based electricity) to produce electricity for BSI unit^b Diesel generator was used to generate electricity to operate BSI unit^c Grid electricity was consumed to operate BSI unit

*Direct emissions produced during biochar production process are mentioned in Table A3

developed including half-life, MRT, CSF, and BC_{+100} to estimate time biochar-carbon remain or degrade in the soil. This study used BC_{+100} to estimate the biochar carbon sequestered in the soil. Equation 1 was used to estimate the carbon stored or sequestered in biochar that was applied to the soil.

$$CS_b = 3.67 * C_b * f_b * BC_{+100} \quad (1)$$

where CS_b , C_b , f_b , and BC_{+100} are carbon sequestration potential, carbon content, recalcitrant carbon fraction in biochar, and the percentage of organic C in biochar that remains stable in soil for more than 100 years respectively. The values of C_b are mentioned in Table 3. In this study, biochar was produced from clean woody biomass at higher pyrolysis temperature and thus produced high-quality biochar, i.e., higher carbon content and higher recalcitrant [$f_b=0.97$ (Wang et al. 2016)] carbon in the biochar. Budai et al. (2013) estimated biochar with lower ($H/C_{org} \leq 0.4$) can have BC_{+100} value of 80.5%, i.e., after 100 years of application of biochar in the soil, 80.5% of carbon in the biochar remains stable with the remaining 19.5% returned to the atmosphere.

2.2 Techno-economic analysis

2.2.1 Minimum selling price

In this study, the minimum selling price (MSP) was estimated using a DCFROR model for a projected 10-year lifespan of the three portable systems. The MSP is the sales price for the product at which a system's net present value (NPV) is zero. The major general financial assumptions for the DCFROR model were a 16.5% nominal discount rate (before finance and tax), annual 2% inflation of costs and revenues, and a 40% income tax rate (Sahoo et al. 2019). The capital cost was assumed to finance through both debt [40% of the initial capital cost and annual loan interest (nominal) rate of 6.51% for a term of 5 years] and equity (60% of initial capital cost and for full project planning period of 10 years). A declining balance depreciation of 200% on the assets' values was assumed. All capital and operating cost estimates were adjusted to the US 2019 dollars considering the Chemical Engineering Price of Construction Indices (CEPCI) and the Consumer Price Index (CPI).

The working hours and working days of the portable systems were restricted by the feedstocks' MC and slash burning period, especially for OK. For the base case, it was assumed that the portable systems operated 16 h/day (2 shifts $\times$ 8 h/shift) and 100 days in a year. However, the BSI is equipped with dryers and can handle higher MC biomass; thus, the BSI system can operate all the year. A sensitivity analysis of operating BSI system from 8 h/day to 24 h/day (3 shifts $\times$ 8

h/shift) and 300 days/year was incorporated. Furthermore, it was anticipated that all portable systems operate at 90% of their nameplate capacities throughout their economic lives. Tables 4 and 5 provide the capital and operating costs respectively for the financial analysis.

2.2.2 Capital cost

Equipment's purchase price, useful economic-life, and salvage value are presented in Table 4 which are used for producing biochar in the Pacific Northwest. Portable systems, especially the BSI system, require rigorous site preparation and installation which depends on the number of relocations in a year. Therefore, costs incurred due to site preparation and equipment installation were considered in annual fixed operating costs (not as a part of the fixed capital cost) as relocation cost. Due to the requirement of a smaller land footprint for a portable system or negligible rent for the land near the forest, land purchase or rental cost was excluded in this study. A scaling factor of 0.6 with respect to existing equipment was used to estimate the capital cost for equipment which did not have cost data available for the size used in this study. As shown, the purchase price for the two BSI system biochar machines was substantially higher as a percentage of the total costs compared with the other two systems. Loaders were by far the highest costs for the other production systems.

2.2.3 Operating cost

The fixed operating cost (Table 5) includes relocation, insurance (1.5% of average annual investment), property taxes (0.2% of the equipment purchase price), and repair and maintenance (15% of straight-line depreciation of total capital cost). The number of relocations can vary with biomass availability and the production capacity of portable systems. For consistency, we assumed two relocations in a year (Berry and Sessions 2018). The detailed description of operating costs related to feedstocks procurement, relocations, consumables, labor, packaging, and product transportation is described by Sahoo et al. (2019). Moreover, a detailed description of consumables, especially fuels, is described in section 2, Table 3.

2.3 Biochar policies, scenario, and sensitivity analysis

Subsidies assist in the production of biochar which affects the economic feasibility of these projects. In the US, there are currently around 35 policy programs from different government agencies that directly or indirectly support biochar production (Pourhashem et al. 2019) from commercial production to land reclamation. Most of them are supported by the US Department of Agriculture (USDA). The USDA-

Table 4 Capital costs for portable biochar production systems

	No of units	Equipment	Description	Purchase price (\$)	Economic life (year)	Salvage value (%)	Reference
BSI	1	Front-end loader	Tractor 1023E (17 kW) + loader	15,000	10	20	(Sahoo et al. 2019)
	2	Dryer	Beltomatic 123B (3.6 m × 0.69 m)	45,000	25	20	(Sahoo et al. 2019)
	2	Biochar machine	Biochar Solutions, Inc., 0.5 t/h	340,000	10	20	(Sahoo et al. 2019)
	2	Genset	20 kW, PP20GT gasifier	25,000	10	10	(Sahoo et al. 2019)
	1	Genset	Diesel generator, 40 kW	39,000	10	20	Manufacturer
		BSI, total		<i>\$835,000^a or \$824,000^b or \$785,000^c</i>			
OK	12	Kiln	OK, pyramidal shape	850	10	20	Manufacturer
	6	Chain saw	NA	500	10	20	Assumed
	2	Propane torch	NA	300	5	20	Assumed
	6	Shovel	NA	50	5	20	Assumed
	2	Skid loader	50 kW	32,000	15	10	Manufacturer
		OK, total		<i>\$78,100</i>			
ACB	1	ACB	Fire box, S-330	168,900	10	20	Manufacturer
	1	Swing loader	145 kW, John Deere 2954D	432,000	10	20	Manufacturer
	1	Propane torch	NA	300	5	20	Assumed
		ACB, total		<i>\$601,200</i>			

^a Total capital cost of BSI system with gasifier-based generator

^b Total capital cost of BSI system with diesel generator

^c Total capital cost of BSI system with grid-electricity (no generator required to power the equipment)

sponsored program under Conservation Stewardship Program (CSP) (program named “E384135Z”) provides financial incentives (\$12,600/ha of forest in Washington State) to create biochar from woody debris remaining after fuel reduction harvests or wildfires (USDA-NRCS 2019). We have analyzed the impacts of present grants on the financial performance of making biochar with the three portable systems.

Multiple scenarios (Fig. 2) were considered in this study to compare forest residues’ disposal costs, i.e., make biochar or slash burn. Moreover, the study considered different pathways to make biochar including different portable systems and their unique logistics for conifer forest residues. The scenarios considered in this study were (i) biochar production by forest residue type, (ii) biochar production at near-forest site versus in-town, (iii) biochar production by different production systems, and (iv) biochar production systems with “slash and burn” comparisons considering biogenic carbon accounting.

Sensitivity analyses were conducted to determine critical input parameters impacting biochar’s GW impact and MSP. In every simulation of the LCA and DCFROR models, the changes in the GW impact and MSP were calculated by changing each input parameter by $\pm 20\%$ of base value while keeping other parameters unchanged. Among all input parameters assessed, the bar chart presented the impact of only a few most sensitive ones affecting the results.

3 Results and discussion

3.1 Biochar produced with BSI portable system at near-forest production sites

The cradle-to-grave GW impacts of biochar production with the BSI system at a near-forest location considering different feedstocks quality and sources of power varied from 249 to 1001 kgCO₂eq/t of biochar (Fig. 5). Among all unit operations assessed in the cradle-to-grave LCA of biochar, feedstock processing, and biochar conversion combined contributed 75–95% of total GW impacts. Despite the additional biomass necessary for generating electricity with the gasifier-based generator, the biochar production using the gasifier-based generator substantially reduced (64 – 70%) the GW impact over the diesel generator. Small-chipped pulpwood had a lower GW impact compared with medium-chipped forest residues because forest residues were coarser than pulpwood. In addition, ground and clean forest residues have lower GW impact compared with chipped forest residues. Biochar with higher fixed carbon content offers large and long-term carbon storage potential when it is applied to the soil (Bergman et al. 2016). Among all types of feedstocks, biochar produced from ground-clean and chipped-medium feedstocks had the largest carbon storage potential due to the presence of higher fixed carbon. When the gasifier-based generator was used for onsite

Table 5 Annual operating costs incurred in different production systems

	Descriptions	Units	BSI	OK	ACB	Comments
1	Feedstocks ^a	\$/ODMT	14.0	0	0	(Sahoo et al. 2018)
2	Relocations ^b	\$/year	20,868	684	1,368	(Sahoo et al. 2019)
3	Repair and maintenance ^c	\$/year	14,600	400	1,600	15% of SLD
4	Consumables ^d	\$/year	16,900 (+ 12,100* or + 4,150**)	17,762	40,368	Annual usage of diesel and propane
5	Finished good transportation ^e	\$/ODMT	18.5	18.5	18.5	(Sahoo et al. 2018)
6	Labor ^f	\$/year	170,136	103,958	59,028	Estimated
7	Insurance and miscellaneous ^g	\$/year	16,196	8,890	13,225	Estimated
8	Biochar applied to the soil ^h	\$/ODMT	4.3	4.3	4.3	(Bergman et al. 2016)

^a Biomass transportation and micro-chipping costs were estimated to be \$7.0/dry tonne and \$3.5/dry tonne respectively assuming 36% MC_{wb} of logs and processed treetops (Sahoo et al. 2018)

^b BSI system's relocation cost was adopted from (Sahoo et al. 2019). However, relocations of OK just require a truck for transporting 12 kilns and require about 0.5 h for loading and unloading. The relocation cost was estimated similar to OK except it requires two trucks, one for the air curtain burners and another for the loader

^c A 15% of depreciation (SLD (straight-line depreciation)) cost for BSI system and OK. For air curtain burners, the repair and maintenance cost were estimated as described by the manufacturers (standard maintenance as \$40.28/200 operating hours, \$86.56/month, and \$406.68/year)

^d Consumables included propane, diesel, and water. In the BSI system, propane was used for drying feedstocks and maintains flame in the exhaust stack. Propane was used in OK and ACB to start the fire. Diesel was used in diesel generator (*\$12,100/year excludes diesel consumed in the front end loader) when the BSI system operated with a diesel generator. Electricity was purchased (**\$4,100/year) when the BSI system operated with grid electricity. Diesel is also used in front-end loader (BSI system), skid loader (for OK), and boom loader (for ACB)

^e Biochar transportation is needed when biochar is produced at the near-forest or in-forest sites. The transportation cost of biochar was estimated following methods presented by Sahoo et al. (2018) and considering a chip van truck of volume 98 m³ and a bulk density of 106 kg/m³. The estimated transport cost of biochar including loading cost was estimated to be \$18.5/t of biochar for a travel distance of 50 km between the biochar production site and user

^f Labor cost (BLS 2017) for BSI system was adopted by Sahoo et al. (2019). The OK's crew size included six laborer (\$17.0/h) and two machine operators (\$22.5/h) for skidders. The ACB's crew included a technician (\$50/h) and a driver (\$22.5/h) for the loader. Labor cost includes benefits at 35% of basic salary (BLS 2017; Jones et al. 2013)

^g Miscellaneous includes unpredictable cost, administrative cost, 10% of annual salaries @80,000

^h The cost of biochar application was estimated to be \$4.3/ODMT of biochar spread in the field considering spreader field capacity of 6.4 t/h (Bergman et al. 2016)

generation of electricity to operate the BSI system, biochar produced from medium-chipped- or ground-clean forest residues and applied to the field had a net GHG emission of about 2,017 kgCO₂eq/t of biochar—storing nearly 7 times more than what is emitted to produce the biochar and apply it to the soil. Overall, biochar produced with the BSI system at the near-forest setup and when including the sequestered carbon (more than 100 years), the net GHG emissions ranged from 888 and 2,017 kgCO₂eq/t of biochar applied to the soil.

Figure 6 shows the contribution of various incurred annualized costs and MSP of biochar delivered and applied to soil considering feedstock quality and source of power at the near-forest or remote sites. For all scenarios, the annualized production cost of biochar at the near-forest sites was about \$400,000. Both capital (~ 41%) and labor (~ 38%) costs are the two major cost components of total production cost. The rest of the cost components only share about 20% of the total cost. Due to variations in the throughput (200 – 381 dry kg/h) and biochar yield (11 – 16%), the MSP varied between \$3,000 and \$6,000/dry tonne of biochar which can be comparable

with the current market price of \$1,500 – \$4,200 found in a recent biochar survey by Sasatani and Eastin (2018).

Inspecting the MSPs in Fig. 6, several interesting conclusions can be made. First, biochar produced from ground feedstock had lower MSPs than chipped feedstock due to higher throughput with ground feedstock. Second, cleaner woody biomass feedstock resulted in lower MSPs due to higher throughputs of carbon material due to lower ash content, though this was not as strong as an effect as the feedstock type. Third, biochar produced with a diesel genset has slightly higher MSPs than those produced with the woody biomass-fueled gasifier-based generator, due to electricity generation with diesel genset being more expensive than when produced with woody biomass. Overall, the results suggest the primary driver of MSP was the feedstock type, with ground feedstocks having the lowest MSPs of biochar, which although had higher logistical costs, had enough gain in the throughput to be advantaged over the BSI system in terms of production costs using the assumptions from this model.

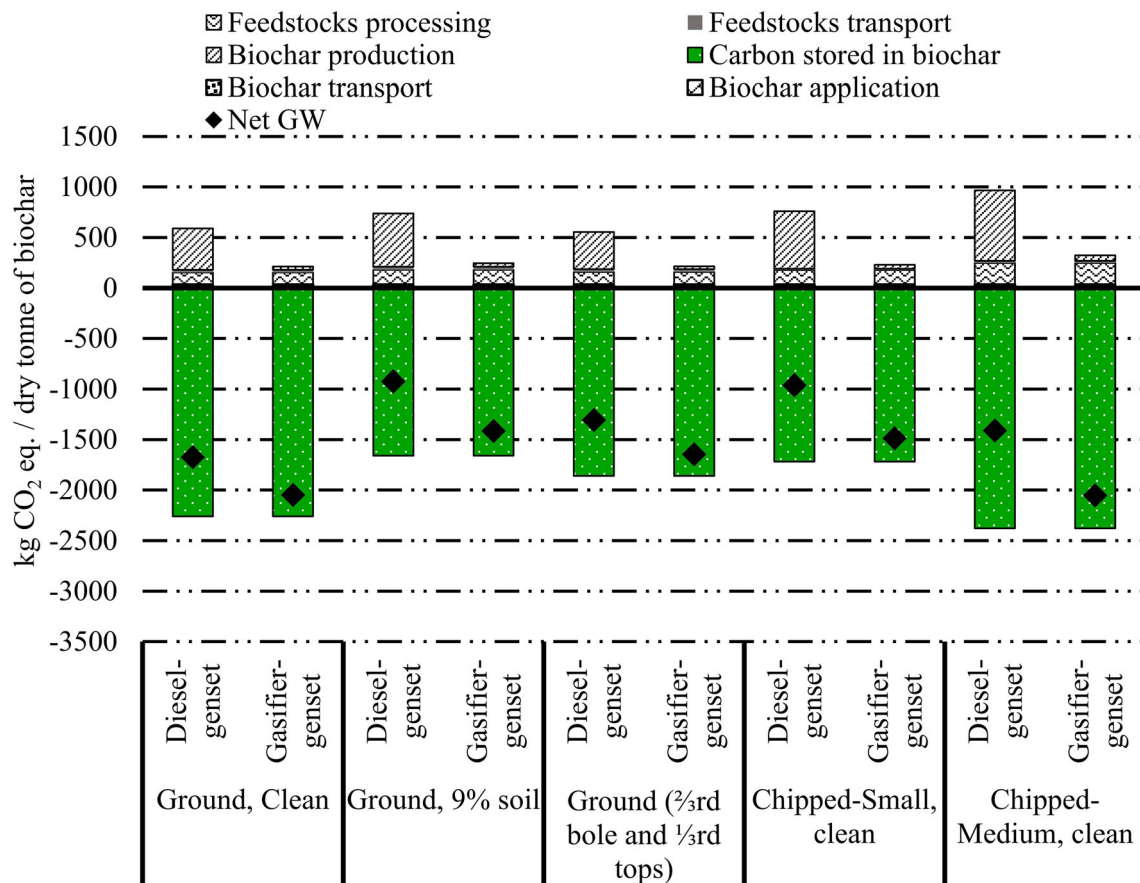


Fig. 5 GW impact of biochar production using the BSI system at a near-forest biochar processing site

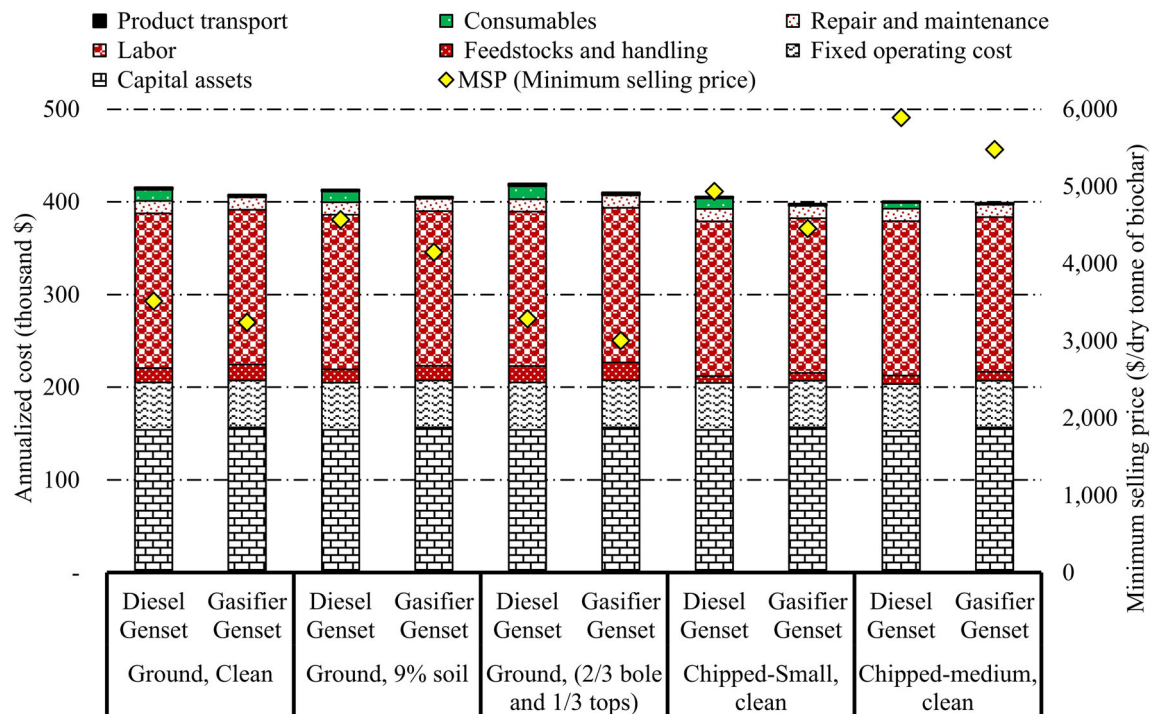


Fig. 6 Annualized production cost and MSP of biochar produced using the BSI system at a near-forest biochar processing site considering 100 days/year of operation

3.2 Biochar produced with BSI portable system at in-town production sites

At the near-forest site, biochar produced from ground-clean and chipped-medium feedstocks with the BSI system performed better considering the net reduction in GW impact. Figure 7 shows the comparative analysis of biochar produced from ground-clean and chipped-medium feedstocks with both BSI systems between near-forest and in-town sites considering different sources of power. Overall, in-town locations had higher GW impact (or lower net GW impact) compared with near-forest locations, irrespective of feedstocks type and sources of power [8–162% for ground-clean feedstocks and 6–99% for chipped-medium feedstocks].

In-town sites provide access to grid electricity for the production of biochar. Grid electricity in the production of biochar had less environmental impacts (30–50% lower GW) compared with the diesel generator scenario. For example, the total GW impact in the production of biochar by transporting pulpwood to the in-town locations (and using the grid electricity as a power source) was much lower (~33–47%) than the total GW impact of biochar produced at the near-forest locations using a diesel generator. However, these benefits were reduced for ground forest residues compared with pulpwood chips, but using a power pallet to generate electricity to operate the BSI system was always the best option (the lowest net GW impact) to produce biochar irrespective of feedstocks and locations. As

expected, the GW impact of biochar increased when the raw material, i.e., forest residues was transported farther, four instead of 2 h from the landing.

It appears that the use of grid electricity to produce biochar at the in-town site had a little benefit over the use of a gasifier-based generator. Compared with the diesel generator, the use of grid electricity lowered the GHG emissions for biochar produced at in-town sites irrespective of feedstocks transport distances (both the 2 and 4-h haul distances). With the increase in transportation distance of forest residues, the total GHG emissions of biochar production increased and resulted in the reduced net GW impact reduction potential of biochar when applied to the soil. Thus, the distance from the forest to the biochar production site can have a substantial impact on the overall supply chain decision, but the carbon storage in biochar was many times higher than the GHG emissions emitted during biochar production including transportation and logistics. Despite the increase in the GW impact due to the transportation of feedstocks from forest to in-town locations, there was a net reduction in the GW impact of $- (1,189 - 2,017)$ kgCO₂eq/t of biochar irrespective of power sources, storing 2 to 2.9 times GHG emission than what was emitted to produce biochar.

Compared with a near-forest site, biochar produced at in-town (2-h and 4-h from the forest) sites both have higher annualized cost and MSPs. Despite increased (60–150%) feedstocks transportation cost for in-town locations, the increase in MSPs is negligible (1–7%) as the feedstocks

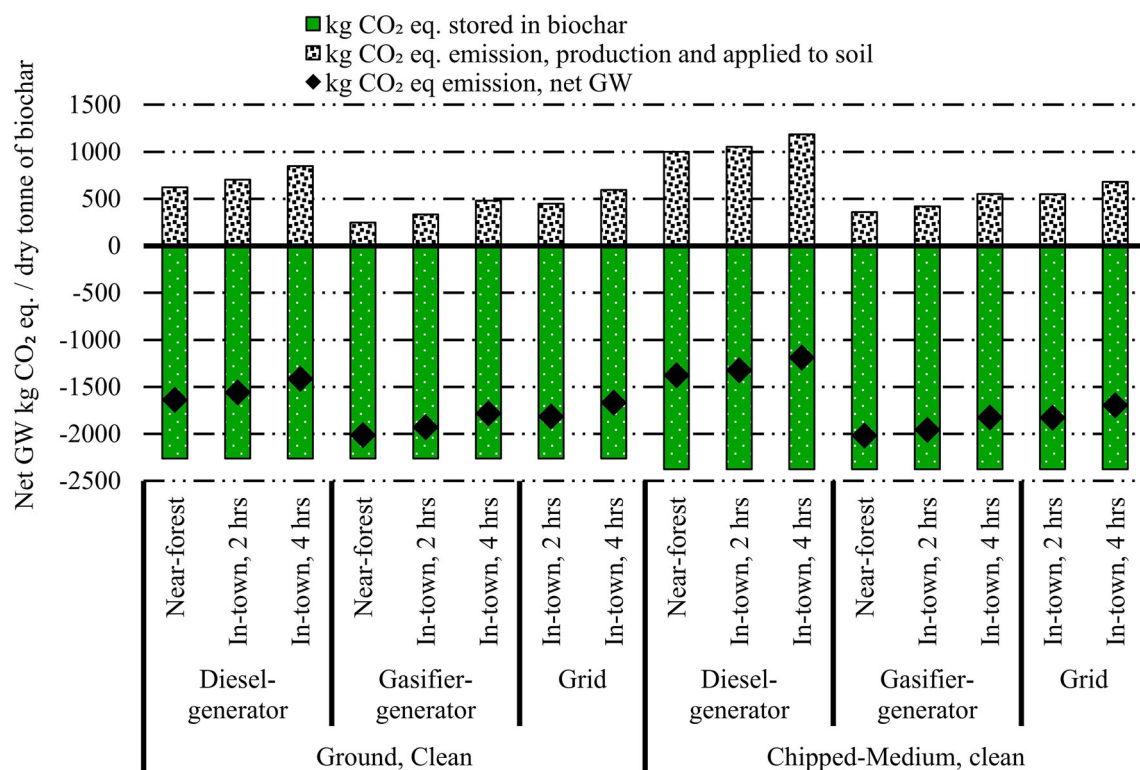


Fig. 7 GW impacts of biochar produced at the in-town sites using the BSI system considering a 2-h transport distance of feedstock from the landing

logistics cost was only 3–10% of total annualized biochar production cost (Fig. 8). The cost of grid power at the in-town location was higher than the cost of power production with power pallet but lower than the diesel genset. As the costliest components were capital and labor, the influence of locations for the BSI system was not a notable factor. If the biochar users are located in-town, an additional transport cost of biochar from near-forest locations to in-town might influence the MSP of biochar produced at a near-forest location, which is discussed later in this article.

3.3 Comparing the performance of portable systems

Figure 9 shows the cradle-to-grave GW impacts of three types of portable systems (i.e., BSI, OK, and ACB) used to make biochar at the near-forest site with respect to per tonne of biochar and per tonne of fixed carbon in the biochar. Overall, for all three systems, the GW impact of biochar applied to soil was varied between 249 and 605 kgCO₂eq/t of biochar (or 315–728 kgCO₂eq/t of fixed carbon in biochar). The GW impact of biochar produced in this study was substantially lower than a centralized system. For example, Azzi et al. (2019) estimated a GW of ~250 kgCO₂eq/t of dry wood

pyrolyzed which is substantially larger than this study (25–40 kgCO₂eq/t of dry woody biomass). Biochar produced with the BSI system generated a lower (~50%) GW impact than the other two portable systems, i.e., the OK and ACB. In the case of BSI systems, 80–90% of total GHG emissions came from feedstocks preparation and forest residues logistics, but ~45% of total GHG emissions can be attributed to feedstocks preparation in both OK and ACB systems. The GW's impact of the biochar production process in the case of OK and ACB was much higher due to emissions of various potent GHGs. Unlike the other two systems, the BSI system also had an emission control system that reduced the direct GHG emissions during pyrolysis and thus lowered its GW impact for the biochar production process.

Considering carbon sequestration through biochar that applied to the soil, the net cradle-to-gate GW impact of biochar from the various forest residues types and portable systems varied between –1,500 and 2,400 kgCO₂eq/t of biochar (–2,900 and 4,400 kgCO₂eq/t of fixed carbon in the biochar).

Figure 10 shows the financial performances of portable systems considering 100 days of operations in a year. The BSI system's annualized cost was highest among all but produced only 136 t of biochar in a year. Labor cost was one of the most

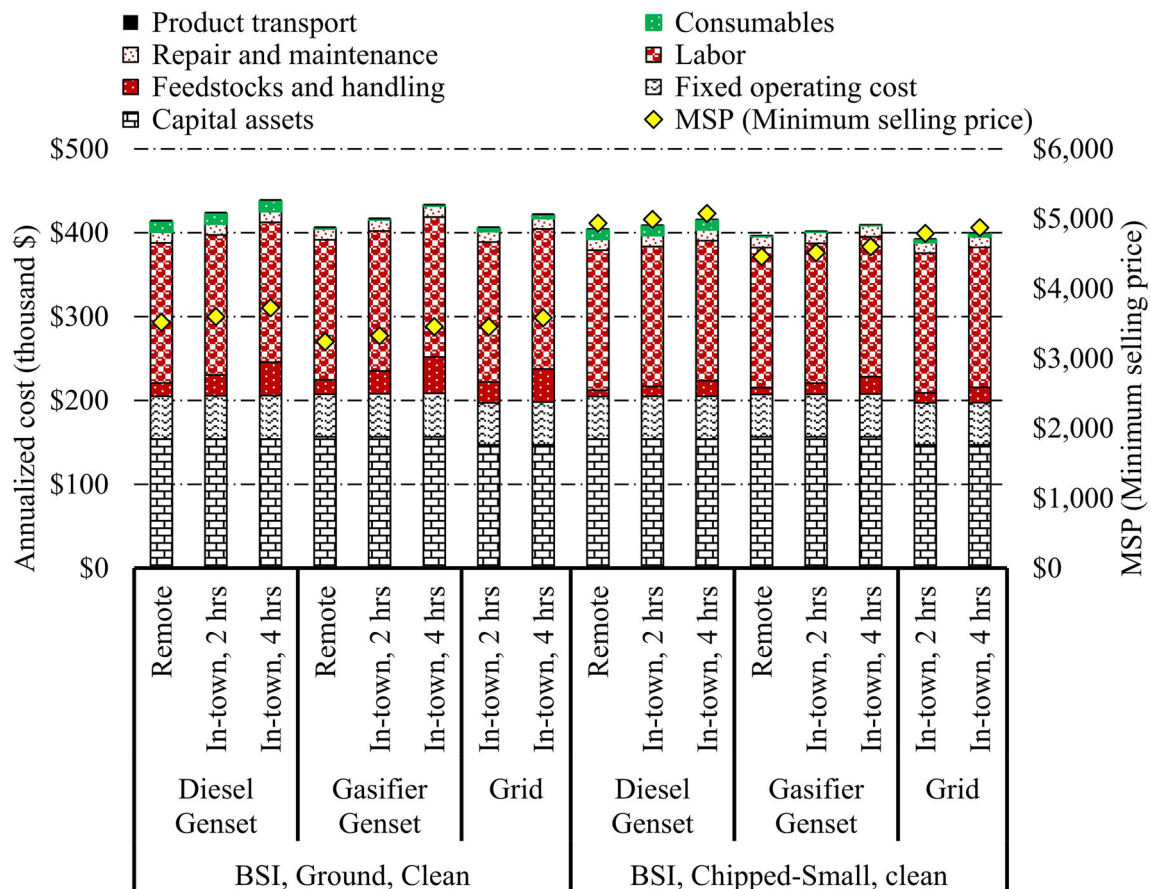


Fig. 8 Comparison of the financial performance of biochar produced at near-forest and in-town sites using the BSI system (feedstocks were transported 2 and 4 h driving distance from the forest)

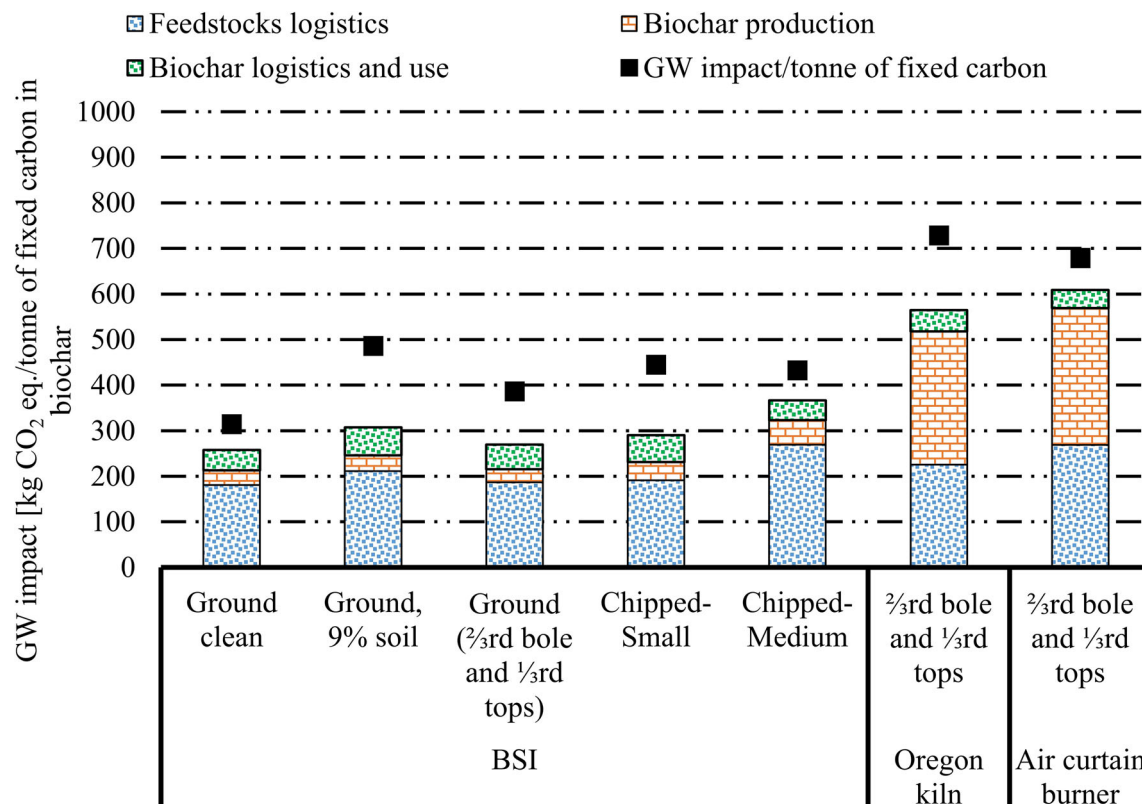


Fig. 9 Cradle-to-grave GW impact of biochar produced from various conifer forest residues and portable systems at the in-forest location (black dots are representing the GW impact per tonne of carbon in the biochar)

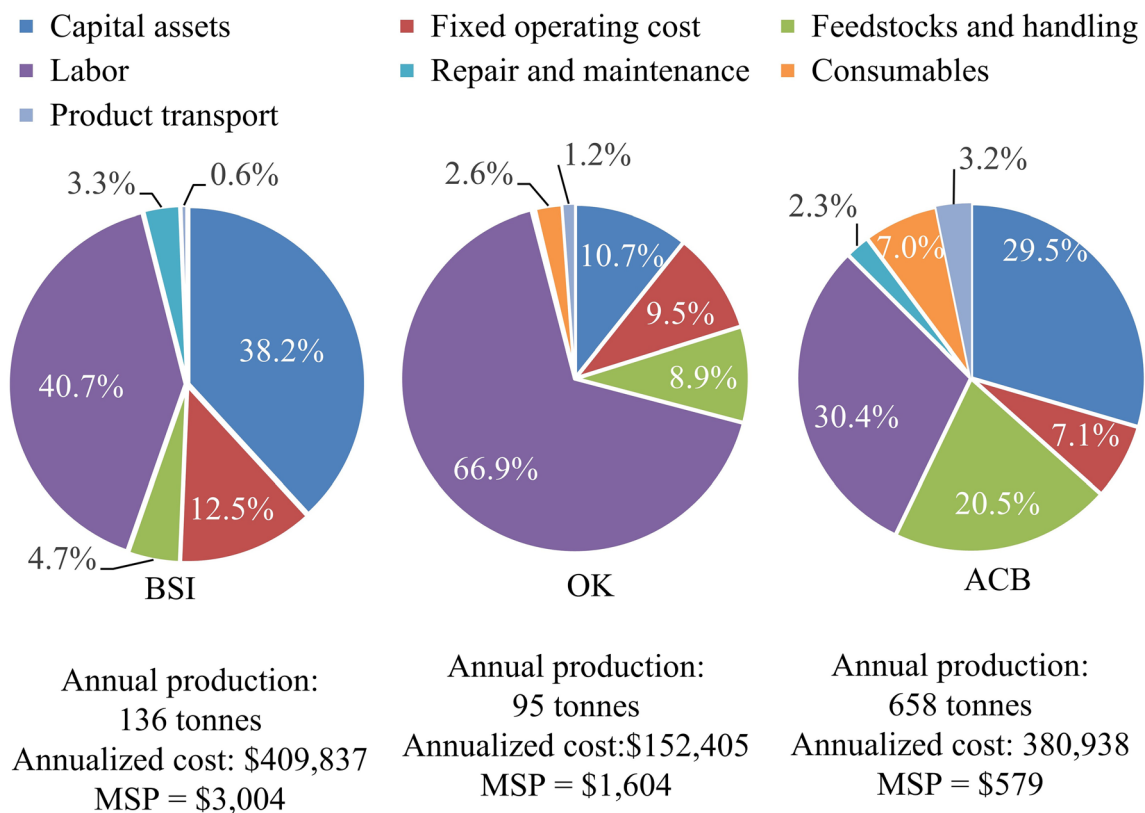


Fig. 10 Contribution of different costs and minimum selling price of biochar produced through three portable systems considering 100 days of operation in a year

dominant costs incurred in the production of biochar irrespective of the type of portable system. Except for OK, capital costs were a significant portion of the total cost for all. As for the ACB, despite the requirement of minimal logistics and feedstocks preparation, about 20% of the total cost incurred from feedstocks logistics. This was due to the inefficient use of the high-cost machines, such as the excavator to feed the forest residues to the ACB. For the OK, labor cost was the only major component of the total annualized cost. Hence, there is an opportunity to use labor and machine more efficiently for OK and ACB respectively to reduce the cost of biochar production. Due to high throughput, the MSP of biochar produced with ACB was ~ 19% and ~ 36% than that of MSPs of BSI and OK respectively. With respect to biochar production, the ACB may be the most economical way to treat forest residues but the ACB had higher (about twice) GW impact compared with the BSI system on a per tonne biochar produced basis.

3.4 Biochar production vs. slash burn

For a given project, LCA can be used to estimate environmental impacts on alternative functional units. The authors in the previously sections reported GW impacts and cost on a product output basis but now will show results on an input basis for the various production systems.

Figure 11 shows the net GW impact (considering fossil and biogenic emissions, carbon stored in the biochar, and carbon absorbed from the atmosphere during plant growth

in residues) on a per unit basis of 1-t forest residues and the break-even cost of using forest residues to produce biochar with three portable systems pile burning of the forest residues. Unlike the other three portable biochar production systems, pile and burn did not produce any biochar. The pile-burn option had a positive GW impact, i.e., not carbon neutral. The biochar produced by OK and ACB emit less GHG emissions and stored more carbon than biochar produced by the BSI machine. Except for the medium-chipped scenario, all biochar production systems had a net negative carbon emission compared with pile-burn (130 kgCO₂eq/t of residues). Similar to wood products in use, the results show the extent to which biochar applied to soil can act as a carbon sink or sequestered carbon due to the presence of decay-resistant carbon, i.e., recalcitrant carbon which has very long mean retention time (i.e., > 100 years) (Wang et al. 2016). However, forest residues left in the soil can degrade very early and during the degradation process, it may release potent GHGs directly while increasing the risk of forest wildfire (Puettmann et al. 2020). Moreover, biochar use in the soil can provide additional benefits including improvement of soil health, moisture-holding capacity, tree growth (Page-Dumroese et al. 2017), crop yield (Liu et al. 2019), and reduce fertilizer need for crop or forest (Li et al. 2018).

Table 6 shows the environmental impacts of using forest residues to make biochar compared with slash burning and included biogenic carbon in the calculation of the GW impact.

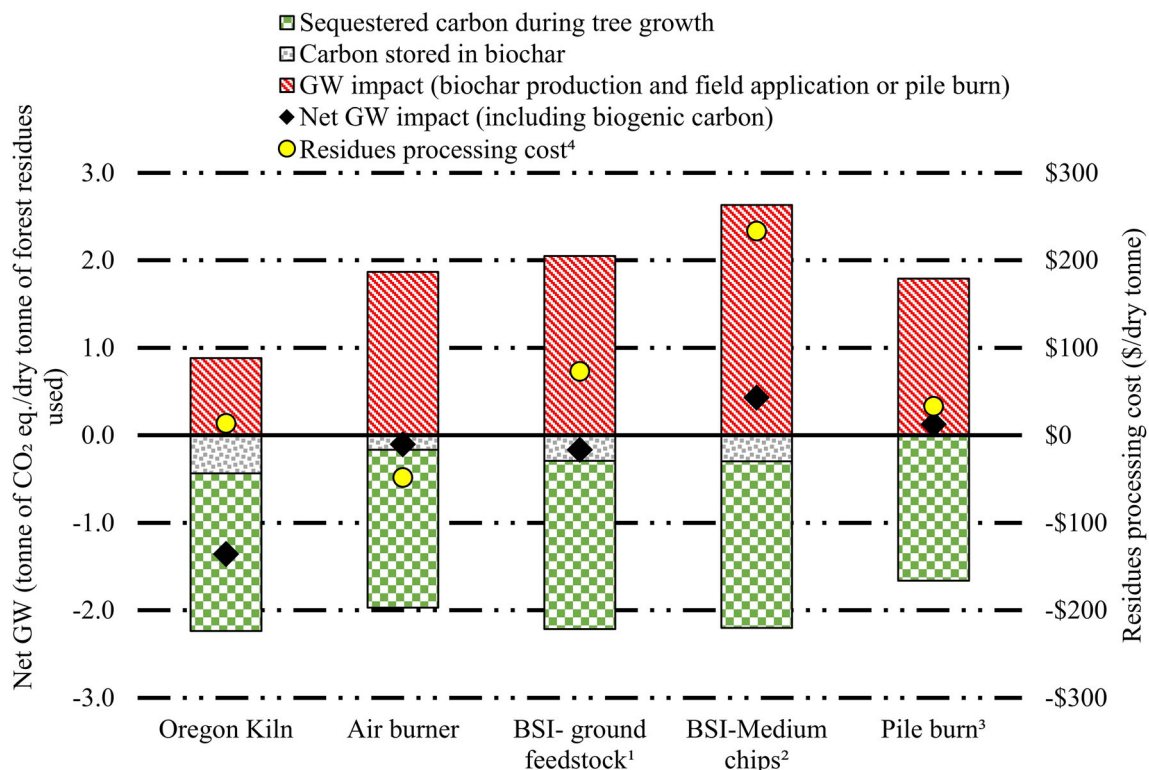


Fig. 11 Net GW (considering biogenic carbon emissions) and cost impacts for biochar production and slash piles burning in the forest.

Table 6 Cradle-to-gate life-cycle impact assessment categories for open burning of slash and biochar production per tonne of forest residue (biogenic carbon included in the estimation of GW impact)

Impact category	Unit	OK	ACB	BSI, (1/3 rd tops + 2/3 rd pulpwood) ground, w/power pallet	BSI, medium chips, w/power pallet	Burn (1/3 rd tops + 2/3 rd pulpwood)
Ozone depletion	kg CFC-11 eq	1.57E-07	8.30E-08	1.26E-09	1.45E-09	5.83E-11
Global warming	kg CO ₂ eq	8.84E+02	1.87E+03	2.04E+03	2.64E+03	1.79E+03
Smog	kg O ₃ eq	2.28E+01	7.65E+00	4.91E+01	6.32E+01	9.78E+01
Acidification	kg SO ₂ eq	6.95E-01	2.28E-01	1.46E+00	1.89E+00	3.64E+00
Eutrophication	kg Neq	5.17E-02	1.75E-02	8.86E-02	1.14E-01	1.77E-01
Carcinogens	CTUh	7.36E-07	2.83E-07	4.59E-07	5.34E-07	1.63E-05
Non-carcinogens	CTUh	7.26E-06	2.80E-06	4.41E-06	5.16E-06	4.18E-07
Respiratory effects	kg PM _{2.5} eq	1.39E-02	5.15E-03	3.10E-02	4.01E-02	4.54E+00
Ecotoxicity	CTUe	1.85E+02	7.13E+01	8.54E+01	1.00E+02	3.67E+01

For most impacts, slash burning had higher environmental impacts than making biochar, especially with the OK and ACB. The ACB and BSI systems' GW impacts were very similar to burning slash piles. Overall, making biochar is an environmentally superior option than pile-burn in every aspect of the impact category and a useful product was produced.

3.5 Impact of incentives/grants on biochar financial performance

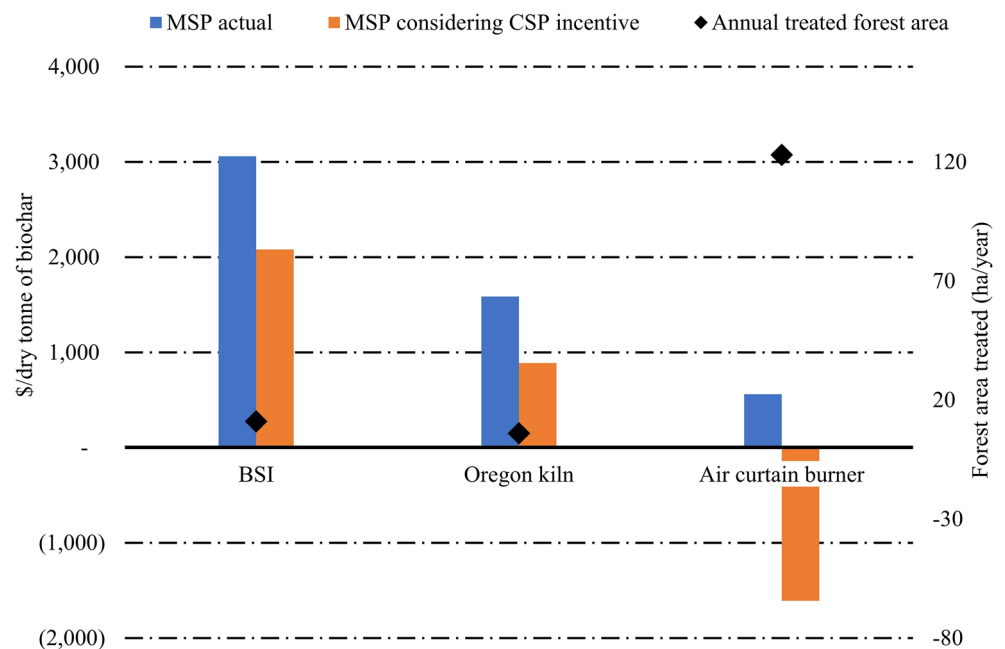
The MSPs of biochar produced through BSI and OK were reduced by 32% and 44% respectively when incorporating CSP financial incentives (Fig. 12). For the ACB, the MSP of biochar became negative when incorporating CSP financial incentives (\$12,600/ha for the State of Washington).

The amount of input forest residues consumed by the BSI and OK was much lower than for the ACB. Thus, the total annual forest land area that could be treated by BSI and OK would be much lower than for an ACB (Fig. 12), and hence, the former portable systems received lower CSP financial incentives. The ACB was able to treat about 123 ha/year of forest land due to its higher throughput compared with the other two portable systems and the annual incentive was estimated to be $\$1.54 \times 10^6$ /year which was more than the annual expenses.

3.6 Sensitivity analysis

Both the environmental and financial performances of any production system are impacted by the input data

Fig. 12 Impact of Conservation Stewardship Program (CSP) financial incentives on the financial performance of biochar production



variability and uncertainties, and the model's assumptions. The most critical factors affecting the environmental (only net GW impact) and financial performances (only MSP) of the biochar production with three portable systems are shown in Fig. 13.

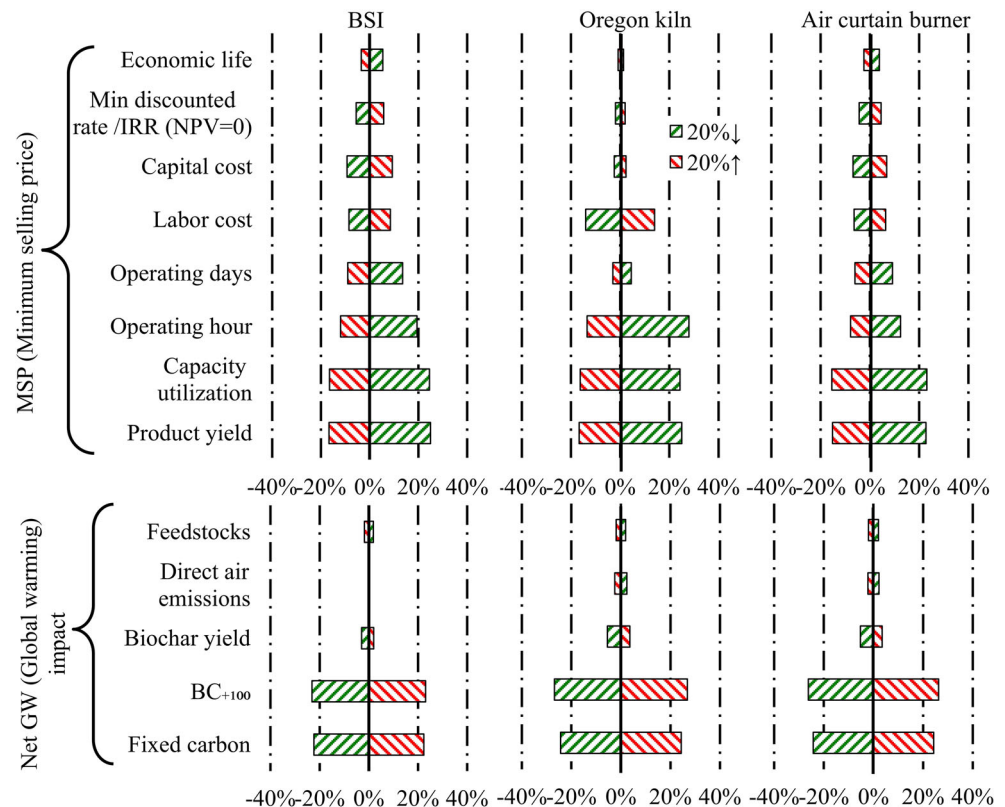
The most sensitive input parameters affecting the MSP were related to the throughput of the portable systems, such as capacity utilization, operating hours in a day, and operating days in a year. A substantial part of working hours was lost due to equipment startup and shutdown (quenching biochar for the OK and ACB). A 24×7 operations and multiple the BSI system with parallel operations could reduce unproductive time such as startup and shutdown of equipment and enhance the daily biochar production system's throughput. The major costs components of biochar production were capital (except OK) and labor, which had significant impacts on MSPs. The sensitive input parameters affecting net GW impact are primarily fixed carbon content. The GW reduction potential of biochar including carbon sequestration was 2–11 times more than the GW impact of biochar production. Therefore, the impact of variations in the input parameters did not show a substantial change in the net GW impact. A 20% variations in the fixed carbon content in the biochar and BC_{+100} (the percentage of organic C in biochar that remains stable in soil for more than 100 years) brought about 22–24% and 23–27% changes in the net GW impact, respectively.

4 Conclusions

The environmental impacts and economic feasibility of producing biochar from forest residues were determined for three portable systems (BSI, OK, and ACB) using a cradle-to-grave LCA and techno-economic analysis (TEA) considering different power sources (diesel generators, wood gasifier-based generators, and grid connection), production sites (near-forestland in-town), and feedstock quality (feedstock size, MC, and ash content.). The mass and energy balances of biochar production and logistical costs were estimated using input data from pilot-scale experimental setups of these portable systems. The LCA model was developed in the SimaPro platform following the ISO14044 guidelines to analyze the environmental performances of biochar production and application to soil in comparison with pile burns. The DCFROR models were developed to estimate the financial performances including the various costs and MSPs of biochar and alternate use of forest residues.

The results from the analyses showed biochar production from forest residues with portable systems was environmentally beneficial and economically feasible. Feedstock quality and type had a substantial impact on the net GW impact and MSP of biochar, especially for the BSI system. Irrespective of feedstock type and locations, the use of a power pallet wood gasifier genset reduced the GW impact of biochar produced through the BSI system by 40–70% compared with a diesel

Fig. 13 Sensitivity analysis of input parameters on the minimum selling prices and global warming impact of biochar produced with portable systems



generator. The GW impact of biochar produced in-town with the BSI system increased by 6–108% compared with near-forest locations based on the electricity sources and hauling time from the forest (2–4 h).

Labor and capital costs were the two major components of total annualized biochar production cost for a BSI system irrespective of feedstock type, locations, and power source. Assuming 100 operating days in a year and without considering biochar logistics, the MSPs of biochar produced with the BSI system varied between \$3,000 and \$6,000/dry tonne of biochar. Biochar produced from ground-and-clean forest residues was 30–50% lower MSP than chipped-residues due to lower throughput in the later. Using the gasifier-based generator to operate the BSI system to produce biochar provided the lowest MSPs compared with either diesel genset or grid connectivity.

Along the supply chain evaluated for the three biochar product systems, the different life-cycle stages resulted in major differences. The estimated cradle-to-grave GW impacts of biochar produced through BSI, OK, and ACB were 214–1,073, 553, and 604 kgCO₂eq/t of biochar applied to the field, respectively. However, overall, when considering the carbon stored in the final product (i.e., biochar) applied to the soil, the net GW impacts were all negative at – (88–2,017), – 1,623, and – 1,944 kgCO₂eq/t of biochar produced with BSI, OK, and ACBs, respectively. This negative result is consistent with a variety of wood products such as lumber produced where the carbon stored in the final product on a CO₂ equivalent basis far outweighed the product production GHG emissions (Bergman et al. 2014; Puettmann et al. 2010). Despite a substantial difference in fixed carbon content in biochar produced from three portable systems, all had negative GW impacts, and differences among the net GW impacts for the systems were small. The MSPs of biochar produced with the OK and ACB were 50% and 20% lower than the BSI system. Despite large capital cost (similar to the BSI system), the MSP of biochar produced with the ACB was the lowest at about \$579/dry tonne of biochar, due to its large throughput.

Given the favorable environmental performances of these portable biochar systems, it is the financial performance that could prevent its commercialization. However, except, for the BSI system, the MSP estimated fell within or lower than the market price of biochar (\$1500–\$4000)(Sasatani and Eastin 2018). Additionally, there are several policies in the US to support the production of biochar, which could substantially improve the financial performance of biochar production for all three portable systems.

In summary, the production of biochar using portable systems and applied to soil appears environmentally beneficial (i.e., negative GW impacts), and potentially economical. Given the vast area of forests requiring restoration, the ACB would be considered the best option given its superior

production capacity. Conversely, given grave concerns surrounding climate change, the BSI system would be preferred because of its GHG profile. The current study provided critical analysis and information to all stakeholders including policymakers, investors, forest owners, and farmers for a better understanding of the use of forest residues to produce biochar using portable systems. Opportunities exist to establish a sustainable bioproduct industry in the US when forest residue collection and processing can be utilized for a useful product to mitigate wildfire and incentives are offered to produce biochar from available forest residues.

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References

- Agegnehu G, Srivastava AK, Bird MI (2017) The role of biochar and biochar-compost in improving soil quality and crop performance: a review. *Appl Soil Ecol* 119:156–170. <https://doi.org/10.1016/j.apsoil.2017.06.008>
- Alanya-Rosenbaum S, Bergman RD (2019) Life-cycle impact and exergy based resource use assessment of torrefied and non-torrefied briquette use for heat and electricity generation. *J Clean Prod* 233: 918–931. <https://doi.org/10.1016/j.jclepro.2019.05.298>
- Alanya-Rosenbaum S, Bergman RD, Ganguly I, Pierobon F (2018) A comparative life-cycle assessment of briquetting logging residues and lumber manufacturing coproducts in Western United States applied engineering in agriculture 34:11–24 <https://doi.org/10.13031/aea.12378>
- Alhashimi HA, Aktas CB (2017) Life cycle environmental and economic performance of biochar compared with activated carbon: a meta-analysis. *Resour Conserv Recycl* 118:13–26. <https://doi.org/10.1016/j.resconrec.2016.11.016>

- Anderson NM, Bergman RD, Page-Dumroese DS (2016) A supply chain approach to biochar systems biochar: a regional supply chain approach in view of mitigating climate change:25-26
- Azzi ES, Karlton E, Sundberg C (2019) Prospective life cycle assessment of large-scale biochar production and use for negative emissions in Stockholm. *Environ Sci Technol* 53:8466–8476. <https://doi.org/10.1021/acs.est.9b01615>
- Badger P, Badger S, Puettmann M, Steele P, Cooper J (2010) Techno-economic analysis: preliminary assessment of pyrolysis oil production costs and material energy balance associated with a transportable fast pyrolysis system. *BioResources*:6
- WTW (2018) Waste to wisdom: utilizing forest residues for the production of bioenergy and biobased products. Final Report. 78p.
- Bergman R, Gu H, Alanya-Rosenbaum S, Liang S (2019) Comparative life-cycle assessment of biochar activated carbon and synthesis gas electricity with commercially available alternatives Gen Tech Rep FPL-GTR-270 Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory 32 p 270:1-32
- Bergman R, Puettmann M, Taylor A, Skog KE (2014) The carbon impacts of wood products. *For Prod J* 64:220–231. <https://doi.org/10.13073/FPJ-D-14-00047>
- Bergman RD, Zhang H, Englund K, Windell K, Gu H (2016) Estimating GHG emissions from the manufacturing of field-applied biochar pellets. In: *Proceedings of the 59th International Convention of Society of Wood Science and Technology*, pp 1-11
- Berrill J-P, Han H-S (2017) Carbon, harvest yields, and residues from restoration in a mixed forest on California's coast range forest science 63:128-135
- Berry M, Sessions J (2018) The economics of biomass logistics and conversion facility mobility: an Oregon case study. *Appl Eng Agric* 34:57–72. <https://doi.org/10.13031/aea.12383>
- BLS (2017) Occupational employment statistics. Bureau of labor statistics. <https://data.bls.gov/oes/#/occGeo/One%20occupation%20for%20multiple%20geographical%20areas>. Accessed 08/28/2017 2017
- Brown AL, Brady PD A techno-economic analysis of the potential for portable pyrolysis in Northern New Mexico forests. In: *Proceedings of the ASME 2012 Summer Heat Transfer Conference*, Rio Grande, Puerto Rico, July 8-12 2012. vol 44786. pp 161-171. <https://doi.org/10.1115/HT2012-58113>
- Budai A et al. (2013) Biochar carbon stability test method: an assessment of methods to determine biochar carbon stability International Biochar Initiative:1-10
- Carrasco JL, Gunukula S, Boateng AA, Mullen CA, DeSisto WJ, Wheeler MC (2017) Pyrolysis of forest residues: an approach to techno-economics for bio-fuel production. *Fuel* 193:477–484. <https://doi.org/10.1016/j.fuel.2016.12.063>
- Chen X, Zhang H, Xiao R (2018) Mobile autothermal pyrolysis system for local biomass conversion: process simulation and techno-economic analysis. *Energy Fuel* 32:4178–4188. <https://doi.org/10.1021/acs.energyfuels.7b03172>
- Clare A, Shackley S, Joseph S, Hammond J, Pan G, Bloom A (2015) Competing uses for China's straw: the economic and carbon abatement potential of biochar. *GCB Bioenergy* 7:1272–1282. <https://doi.org/10.1111/gcbb.12220>
- Cook PS, Becker DR (2017) State funding for wildfire suppression in the Western US. University of Idaho, Moscow, Idaho
- Cornelissen G, Pandit NR, Taylor P, Pandit BH, Sparrevik M, Schmidt HP (2016) Emissions and char quality of flame-curtain “Kon Tiki” kilns for farmer-scale charcoal/biochar production. *PLoS One* 11: e0154617. <https://doi.org/10.1371/journal.pone.0154617>
- Dutta B, Raghavan V (2014) A life cycle assessment of environmental and economic balance of biochar systems in Quebec. *Int J Energy Environ Eng* 5:106
- Fann N, Alman B, Broome RA, Morgan GG, Johnston FH, Pouliot G, Rappold AG (2018) The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Sci Total Environ* 610-611:802–809. <https://doi.org/10.1016/j.scitotenv.2017.08.024>
- Field JL, Keske CMH, Birch GL, Defoort MW, Francesca Cotrufo M (2013) Distributed biochar and bioenergy coproduction: a regionally specific case study of environmental benefits and economic impacts. *GCB Bioenergy* 5:177–191. <https://doi.org/10.1111/gcbb.12032>
- Gu H, Bergman R (2016) Life-cycle assessment of a distributed-scale thermochemical bioenergy conversion system. *Wood Fiber Sci* 48: 129–141
- Gu H, Bergman R (2017) Cradle-to-grave life cycle assessment of syngas electricity from woody biomass residues. *Wood Fiber Sci* 49:177–192
- Gu H, Bergman R, Anderson N, Alanya-Rosenbaum S (2018) Life cycle assessment of activated carbon from woody biomass. *Wood Fiber Sci* 50:229–243
- Gurwick NP, Moore LA, Kelly C, Elias P (2013) A systematic review of biochar research, with a focus on its stability in situ and its promise as a climate mitigation strategy. *PLoS One* 8:e75932
- Hammond J, Shackley S, Sohi S, Brownsort P (2011) Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK. *Energy Policy* 39:2646–2655. <https://doi.org/10.1016/j.enpol.2011.02.033>
- Homagain K, Shahi C, Luckai N, Sharma M (2015) Life cycle environmental impact assessment of biochar-based bioenergy production and utilization in Northwestern Ontario, Canada. *J For Res* 26: 799–809. <https://doi.org/10.1007/s11676-015-0132-y>
- Hudiburg TW, Law BE, Wirth C, Luyssaert S (2011) Regional carbon dioxide implications of forest bioenergy production. *Nat Clim Chang* 1:419–423. <https://doi.org/10.1038/nclimate1264>
- Inoue Y, Mogi K, Yoshizawa S (2011) Properties of cinders from red pine, black locust and henon bamboo. Ina Carbonization Laboratory Co., Ltd
- ISO (2006a) Environmental management: life cycle assessment; principles and framework. international organization for standardization,
- ISO (2006b) Environmental management: life cycle assessments: requirements and guidelines. International Standardization Organization,
- Jones SB et al. (2013) Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels: fast pyrolysis and hydrotreating bio-oil pathway. Pacific Northwest National Laboratory (PNNL), Richland, WA (US),
- Kuppens T, Van Dael M, Vanreppelen K, Carleer R, Yperman J, Schreurs S, Van Passel S (2014) Techno-Economic Assessment of pyrolysis char production and application—a review. *Chem Eng Trans*:37
- Lee C, Erickson P, Lazarus M, Smith G (2010) Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues. Stockholm Environment Institute, Stockholm, Sweden
- Leng L et al (2019) Biochar stability assessment by incubation and modelling: methods, drawbacks and recommendations. *Sci Total Environ* 664:11–23. <https://doi.org/10.1016/j.scitotenv.2019.01.298>
- Li D et al (2020) Biochar-related studies from 1999 to 2018: a bibliometrics-based review. *Environ Sci Pollut Res* 27:2898–2908. <https://doi.org/10.1007/s11356-019-06870-9>
- Li Y et al (2018) Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. *J Soils Sediments* 18:546–563. <https://doi.org/10.1007/s11368-017-1906-y>
- Liu X, Mao P, Li L, Ma J (2019) Impact of biochar application on yield-scaled greenhouse gas intensity: a meta-analysis. *Sci Total Environ* 656:969–976. <https://doi.org/10.1016/j.scitotenv.2018.11.396>
- LTS (2019) DATASmart LCI Package. <https://ltsexperts.com/services/software/datasmart-life-cycle-inventory/>. Accessed 05/01/2019
- Lu HR, El Hanandeh A (2019) Life cycle perspective of bio-oil and biochar production from hardwood biomass; what is the optimum mix and what to do with it? *J Clean Prod* 212:173–189. <https://doi.org/10.1016/j.jclepro.2018.12.025>

- Mirkouei A, Haapala KR, Sessions J, Murthy GS (2017) A mixed biomass-based energy supply chain for enhancing economic and environmental sustainability benefits: a multi-criteria decision making framework. *Appl Energy* 206:1088–1101. <https://doi.org/10.1016/j.apenergy.2017.09.001>
- Mirkouei A, Mirzaie P, Haapala KR, Sessions J, Murthy GS (2016) Reducing the cost and environmental impact of integrated fixed and mobile bio-oil refinery supply chains. *J Clean Prod* 113:495–507. <https://doi.org/10.1016/j.jclepro.2015.11.023>
- Muñoz E, Curaqueo G, Cea M, Vera L, Navia R (2017) Environmental hotspots in the life cycle of a biochar-soil system. *J Clean Prod* 158: 1–7. <https://doi.org/10.1016/j.jclepro.2017.04.163>
- Noss RF, Franklin JF, Baker WL, Schoennagel T, Moyle PB (2006) Managing fire-prone forests in the western United States *Frontiers in Ecology and the Environment* 4:481–487 doi:<https://doi.org/10.1890/1540-9295>
- Oneil EE, Cornnick JM, Rogers LW, Puettmann ME (2017) Waste to wisdom: integrating feedstock supply, fire risk and life cycle assessment into a wood to energy framework. Final Report on Task 4.2, 4.7 and 4.8.
- Page-Dumroese DS, Anderson NM, Windell KN, Englund K, Jump K (2016) Development and use of a commercial-scale biochar spreader vol 354. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO
- Page-Dumroese DS, Busse MD, Archuleta JG, McAvoy D, Roussel E (2017) Methods to reduce forest residue volume after timber harvesting and produce black carbon. *Scientifica* 2017:8–8. <https://doi.org/10.1155/2017/2745764>
- Parkhurst KM, Saffron CM, Miller RO (2016) An energy analysis comparing biomass torrefaction in depots to wind with natural gas combustion for electricity generation. *Appl Energy* 179:171–181. <https://doi.org/10.1016/j.apenergy.2016.05.121>
- Pereira PEL, Suddick EC, Six J (2016) Carbon abatement and emissions associated with the gasification of walnut shells for bioenergy and biochar production. *PLoS One* 11:e0150837. <https://doi.org/10.1371/journal.pone.0150837>
- Peters JF, Iribarren D, Dufour J (2015) Biomass pyrolysis for biochar or energy applications? A Life Cycle Assessment. *Environ Sci Technol* 49:5195–5202. <https://doi.org/10.1021/es5060786>
- Polagye BL, Hodgson KT, Malte PC (2007) An economic analysis of bio-energy options using thinnings from overstocked forests. *Biomass Bioenergy* 31:105–125. <https://doi.org/10.1016/j.biombioe.2006.02.005>
- Pourhashem G, Hung SY, Medlock KB, Masiello CA (2019) Policy support for biochar: review and recommendations 11:364–380 <https://doi.org/10.1111/gcbb.12582>
- PRéConsultants (2019) SimaPro 8 life-cycle assessment software package. Version 8. Plotter 12. <https://simapro.com/>.
- Puettmann M, Sahoo K, Wilson K, Oneil E (2020) Life cycle assessment of biochar produced from forest residues using portable systems. *J Clean Prod*:250. <https://doi.org/10.1016/j.jclepro.2019.119564>
- Puettmann M, Wilson K, Oneil E (2017a) Waste to wisdom: integrating feedstock supply, fire risk and life cycle assessment into a wood to energy framework.
- Puettmann M, Wilson K, Oneil E (2017b) Waste to wisdom: life cycle assessment of biochar from postharvest forest residues.
- Puettmann M, Wilson K, Oneil E (2018) Waste to wisdom: life cycle assessment of biochar from post-harvest forest residues.
- Puettmann ME, Wagner FG, Johnson L (2010) Life cycle inventory of softwood lumber from the inland northwest US. *Wood Fiber Sci* 42: 52–66
- Qambrani NA, Rahman MM, Won S, Shim S, Ra C (2017) Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: a review renewable and sustainable energy reviews 79:255–273. <https://doi.org/10.1016/j.rser.2017.05.057>
- Ramachandran S, Yao Z, You S, Massier T, Stimming U, Wang C-H (2017) Life cycle assessment of a sewage sludge and woody biomass co-gasification system. *Energy* 137:369–376. <https://doi.org/10.1016/j.energy.2017.04.139>
- Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J (2010) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environ Sci Technol* 44:827–833. <https://doi.org/10.1021/es902266r>
- Ronsse F, van Hecke S, Dickinson D, Prins W (2013) Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *GCB Bioenergy* 5:104–115. <https://doi.org/10.1111/gcbb.12018>
- Rosas JG, Gómez N, Cara J, Ubalde J, Sort X, Sánchez ME (2015) Assessment of sustainable biochar production for carbon abatement from vineyard residues. *J Anal Appl Pyrolysis* 113:239–247. <https://doi.org/10.1016/j.jaap.2015.01.011>
- Sahoo K (2017) Sustainable design and simulation of multi-feedstock bioenergy supply chain. University of Georgia
- Sahoo K, Bilek E, Bergman R, Kizha AR, Mani S (2018) Economic analysis of forest residues supply chain options to produce enhanced-quality feedstocks Biofuels. *Bioproducts Biorefining (BioPr)* 12
- Sahoo K, Bilek E, Bergman R, Mani S (2019) Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. *Appl Energy* 235:578–590. <https://doi.org/10.1016/j.apenergy.2018.10.076>
- Sasatani D, Eastin IL (2018) Demand curve estimation of locally produced woody biomass products *Applied Engineering in Agriculture* 34:145–155 doi: 10.13031/aea.1239
- SERC (2016) Biochar testing and results report waste to wisdom: task 3. Schatz Energy Research Center (SERC),
- Severy M, Carter D, Chamberlin C, Jacobson A (2016) Biochar testing results report. Humboldt State University
- Severy MA, David JC, Kyle DP, Anthony JE, Arne EJ (2018) Performance and emissions control of commercial-scale biochar production unit *Applied Engineering in Agriculture* 34:73–84 <https://doi.org/10.13031/aea.12375>
- Shackley S, Hammond J, Gaunt J, Ibarrola R (2011) The feasibility and costs of biochar deployment in the UK. *Carbon Management* 2:335–356. <https://doi.org/10.4155/cmt.11.22>
- Singh BP, Cowie AL, Smernik RJ (2012) Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environ Sci Technol* 46:11770–11778. <https://doi.org/10.1021/es302545b>
- Stein SM et al. (2013) Wildfire, wildlands, and people: understanding and preparing for wildfire in the wildland-urban interface-a forests on the edge report vol 299. US Department of Agriculture, Forest Service, Rocky Mountain Research Station. , Fort Collins, CO.
- US-EPA (2012) Tool for the reduction and assessment of chemical and other environmental impacts (TRACI)–TRACI version 2.1 user’s guide. Environmental Protection Agency, Cincinnati, OH, US
- USDA-NRCS (2019) Conservation enhancement activity, E384135Z. United States Department of Agriculture. Natural Resources Conservation Service, Washington, D.C., US
- Wang J, Xiong Z, Kuzyakov Y (2016) Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy* 8: 512–523. <https://doi.org/10.1111/gcbb.12266>
- Wang Z, Dunn JB, Han J, Wang MQ (2014) Effects of co-produced biochar on life cycle greenhouse gas emissions of pyrolysis-derived renewable fuels. *Biofuel Bioprod Biorefining* 8:189–204. <https://doi.org/10.1002/bbb.1447>
- Wilson K (2017) Converting shelterbelt biomass to biochar. wilson biochar associates,
- Wright MM, Brown RC, Boateng AA (2008) Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch

liquids biofuels, bioproducts and biorefining 2:229–238. <https://doi.org/10.1002/bbb.73>

Wrobel-Tobiszewska A, Boersma M, Sargison J, Adams P, Jarick S (2015) An economic analysis of biochar production using residues from Eucalypt plantations. *Biomass Bioenergy* 81:177–182. <https://doi.org/10.1016/j.biombioe.2015.06.015>

Yazan DM, van Duren I, Mes M, Kersten S, Clancy J, Zijm H (2016) Design of sustainable second-generation biomass supply chains.

Biomass Bioenergy 94:173–186. <https://doi.org/10.1016/j.biombioe.2016.08.004>

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