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A techno-economic analysis of biochar production and the bioeconomy for orchard biomass

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ABSTRACT

It is well established that the global practice of burning crop residues, such as orchard biomass, harms human health and the environment. A bioeconomy for orchard biomass may reduce open burning, facilitate the recovery of nutrients that improve soil health, and boost economic growth. We present a techno-economic analysis for converting orchard waste into biochar, a charcoal-like substance that shows promise for improving soil health, but that is considered an experimental product with emerging efficacy and limited market demand. We impute values derived from a cost analysis of biochar production in California's Central Valley into a regional economic input-output model to demonstrate economic growth and a bioeconomy for biochar made with orchard waste. Results from a stochastic Monte Carlo simulation show a probable range of biochar production costs between \$448.78 and \$1,846.96 (USD) Mg^{-1}, with 90% probability that costs will range between \$571 and \$1,455 Mg^{-1}. A sensitivity analysis shows that production costs are most responsive to biochar production rates. A modifiable Excel-based biochar enterprise budget that includes fixed and variable biochar production costs is provided as Supplementary Material. The regional economic analysis demonstrates positive economic growth as defined by job creation, labor compensation, value-added product, and gross output. Stochastic cost estimates and net positive regional economic impacts support economic feasibility of a circular bioeconomy for waste orchard biomass when coupled with governmental policy initiatives. Results may contribute to developing a circular bioeconomy for biochar and orchard biomass in the study region and elsewhere in the world.

1. Introduction

The agricultural practice of burning crop residues serves as one of the greatest sources of greenhouse gas emissions (GHG) and deleterious respiratory human health impacts worldwide (Bhuvaneshwari et al., 2019; Intergovernmental Panel on Climate Change, 2007; Hou et al., 2019). Crop residues are carbon-based materials such as orchard and vineyard pruning, straw, nutshells, pits, and hulls, generated during crop harvesting and processing (Adhikari et al., 2018; Mohammed et al., 2018). Crop production and crop residue burning have risen to keep pace with accelerated global food demand and population, which has grown three-fold over the past 50 years and is expected to continue in upcoming decades (Food and Agriculture Organization (FAO), 2017; Cherubin et al., 2018; Lal, 2005). The FAO (2020) notes that crop residue burning has risen over the past twenty years across all continents except Oceania. Over the ten-year period from 2003 to 2013, crop residues rose by one-third worldwide, totaling 5 Pg in 2013 (Cherubin et al., 2018; Lal, 2005). Sustainable crop residue management is clearly a global concern.

Crop residue burning is frequently the lowest cost agricultural management option (Hou et al., 2019) to clear fields for the next planting season and to control pests (Raza et al., 2019). Approximately 50% of crop residues are burned before the next farming season (Mohammed et al., 2018). Alternatively, crop residues can be composted for fertilizer or animal bedding, left atop the soil to decompose, or eventually become incorporated into the soil through conservation tillage practices. It follows that open burning may be reduced if crop residues are managed as value-added, rather than waste products.

We propose creating biochar from waste orchard residues as an alternative to reduce open burning and to create a circular bioeconomy for orchard crop residues. Biochar is a charcoal-like, high-carbon substance produced at high temperatures through biomass pyrolysis (Maroušek et al., 2019). Besides significantly reducing health and other negative consequences from less air pollution, experiments and field trials show that, under certain conditions, applying biochar as a soil amendment may increase crop yields and sequester carbon (Li et al.,

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2017). Adding biochar as a soil amendment may reduce soil density and stiffness (Grunwald et al. 2017; Ajayi and Horn, 2016). This may correspondingly reduce soil resistance to plowing and other agro-technical operations, thereby enabling agricultural producers to reduce diesel fuel consumption (Lu et al., 2014). Environmental benefits include reduced nitrous oxide (N_2O) (Liu et al., 2017; Liu et al., 2013; Zhang et al., 2010) carbon dioxide (CO_2) and methane (CH_4) emissions (Zhang et al., 2012; Spokas and Reicosky, 2009; Karhu et al., 2011).

Despite preliminary evidence of improved crop yields, managerial cost savings, and environmental benefits, the biochar market is nascent and market transactions are negligible (Campbell et al., 2018; Maroušek et al., 2019). Biochar production has not been a resoundingly profitable business venture, in part due to high fixed and variable costs that are commensurate with a natural monopoly (Skapa, 2012). Insufficient market demand makes cost recovery difficult and creates inability to capitalize on the value of environmental benefits. Biochar has been adopted in rural regions of Asia and Europe (Olarieta et al., 2011; Maroušek et al., 2019), but most households use biochar as a substitute for charcoal (Vochozka et al., 2016; Maroušek et al., 2018). Often, the on-spot profit from using biochar for energy utilization exceeds soil amendment benefits computed over long payback periods (Vochozka et al., 2016; Maroušek et al., 2018). Large acre farmers across the globe remain unaware or skeptical about biochar benefits (Wu et al. 2017; Bezerra et al. 2019), though there is some commercial demand for home gardening (Field et al., 2013). Maroušek et al. (2019) note that many countries either legally restrict or limit biochar use. Meyer et al. (2017) cite tight regulation and performance verification standards where biochar is considered an experimental product despite a substantial pool of patents (Peiris et al., 2017) and two decades of a burgeoning body of literature promoting the product (El-Naggar et al., 2019).

Though most commercial biochar enterprises are not yet financially viable (Hašková, 2017), this could quickly change with increasingly rigorous GHG emission regulation, and increased biochar demand due to emerging soil health and crop yield efficacy, and falling costs that typically accompany new technologies (Keske et al., 2020; Mohan et al., 2018; Ennis et al., 2012; Maroušek et al., 2019; Maroušek et al., 2020; Li et al., 2017; Grunwald et al., 2017; Ajayi and Horn, 2016; Mardoyan and Braun, 2015). Once net benefits of biochar production and adoption are shown as cost competitive management alternatives to crop residue burning, a circular bioeconomy for biochar production can emerge. To get started, the transition to a circular bioeconomy will likely require a targeted financial investment.

With the goal of improving the cost-effectiveness of biochar production and advancing the nascent market for biochar production, this paper presents a techno-economic analysis of biochar production costs for orchard waste in California's Central Valley. This region has approximately 8% of the U.S. agricultural output, and 25% of the nation's food is produced here, including a high percentage of the nation's tree nuts and nearly 100% of almonds (Faunt et al., 2009). We conduct a Monte Carlo simulation to demonstrate the impacts of uncertainty on biochar production from orchard crop residues to reduce production risk and foster entrepreneurship. We demonstrate that a circular bioeconomy from orchard waste is feasible in the study region, by imputing biochar production values calculated through an enterprise budget into a regional IMpact Analysis for PLANning model (IMPLAN, 2021) to evaluate the economic impacts of biochar production on gross output, income, employment, and value-added output in selected counties in the case study region with orchard biomass and biochar production capacity.

If a bioeconomy for biochar production from orchard waste is shown to be economically viable in the study region as an alternative to crop residue burning, there is potential to expand a bioeconomy for biochar elsewhere in the world where there is a critical need to reduce biomass burning, improve soil health, and reduce GHG emissions. To the best of our knowledge, no study provides cost estimates for biochar production under uncertainty with the goal of establishing a bioeconomy. We hypothesize that a range of feasible cost estimates that consider uncertainties associated with biochar production, and that demonstrate value-added product, will foster a bioeconomy.

In the sections that follow, first, we elaborate on biochar's potential to contribute to a circular bioeconomy. Policies relevant to the study region's agricultural waste management and biochar production are also discussed. Materials and methods are in section 3, while section 4 contains results of the stochastic analysis and regional economic analysis of biochar production. Conclusions are presented in Section 5.

2. Biochar's contribution to a bioeconomy

The Linear Economy, comprised of the traditional 'take-make-use-dispose' model of production and consumption, needs to be reworked for agricultural production to keep pace with the world's projected population and increased demand for food. Burning waste crop residues may be a cost-effective management option in a linear model that overlooks adverse environmental effects and biomass nutrients. Given the anticipated scale for global food production and GHG mitigation, it's unlikely that farmers and society will be able to ignore these costs and benefits for much longer.

The European Commission Circular Economy Strategy and "Closing the Loop" Action Plan (European Commission, 2015) note the high value of bio-based resources and biochar specifically that may lead to a circular bioeconomy (Kourmentza et al., 2018; European Commission, 2012). A "circular bioeconomy" is defined as the overlap of the circular economy and bioeconomy (Carus and Dammer, 2018), an innovative research-based approach to optimize the sustainable management and utilization of bio-based resources (Rajesh Banu et al., 2020). Carus and Dammer (2018) suggest that the European Union's 2012 bioeconomy and 2015 circular economy were both connected to biologically originated products, biomass, and food waste. The Institute for European Environmental Policy (2018) contends that the delivery of a circular bioeconomy was created to fulfill the United Nation's Sustainable Development Goals (SDGs) and commitments to both sustainable consumption and reduced GHG emissions.

Though biochar fits well in the circular bioeconomy concept, economic viability and market competitiveness are necessary to facilitate broader scale biochar production and agricultural sector adoption. Achieving a better understanding of production costs helps entrepreneurs to develop a competitive advantage in biochar production, and eventually drive demand for the bioeconomy. Fear of failure is an obstacle to entrepreneurship and new product adoption (Nefzi, 2018); cost data and uncertainty models like those presented in our analysis, may address such concerns. Technological innovation can help shorten production time, leading to cost competitiveness and higher profit (Urbancova, 2013). To this point, our study proposes to produce biochar locally, in rural locations using portable pyrolysis units instead of a centralized facility. The mobile pyrolysis technical innovation may improve production efficiencies by reducing feedstock transportation costs in rural regions where food is grown. Since there is a high concentration of tree nut production and biomass burning in the study region (McCarty et al., 2009), the enterprise budget production, stochastic analysis, and a regional economic model provides proof of concept testing that may reduce uncertainty and facilitate biochar production that can be replicated with orchard biomass elsewhere. In sum, our study adds to the global interest in advancing biochar production (Qambrani et al., 2017) and improving cost competitiveness of biochar production to facilitate a bioeconomy.

2.1. Study area

California's Central Valley serves as a relevant case study due to the region's high agricultural productivity with orchard crops specifically, high prevalence of open burning of crop residue, and increasingly rigorous air quality regulation standards. Conditions are ripe to establish a bioeconomy from crop residue.

California state agencies have implemented numerous policies to reduce open burning, though it remains the state's most common crop residue management practice. Senate Bill-705 requires a valid permit designated by the State Air Resources Board to burn agricultural residues (California Senate Bill No. 705, 2003) and Smoke Management Regulations provide guidelines to air quality management districts to control agricultural residue burning (Title 17 of the California Code of Regulations, 2001). Simultaneously, a series of laws enacted in California target 40% and 80% reductions in the state's GHG emissions including those produced by agricultural crop residues, from 1990 levels by 2030 and 2050 with the hope of mitigating global climate change (Keske, 2020).

Despite these regulations, alarming air pollution levels in the Central Valley continue, in part due to the high biomass transportation costs and poor economic feasibility for value-added biomass products. Twenty-three solid-fuel biomass power plants operate in 17 counties across California with a capacity of producing approximately 532 MW of electricity, though biomass power plants are shutting down periodically due to the high expenses of transporting biomass from diffuse sources (Mayhead and Tittmann, 2012). Technological innovation, such as mobile pyrolysis units, holds promise for processing crop residues on site to avoid transportation costs, and to potentially generate value-added product. California is known as a leader for implementing new environmental policies and facilitating entrepreneurship (Vogel, 2019). Taken together, employing policies that support converting agricultural waste into biochar encourages entrepreneurship that can lay the foundation for the global use of biochar.

2.2. U.S. policies supporting biochar production

Policies that encourage biochar production may nudge the developing market and entrepreneurship until economies of scale can be achieved for broader scale adoption. Currently, there are 35 U.S. policy programs that provide financial incentives for biochar production, including loans, non-financial policy support, and research and development funding (Pourhashem et al., 2019), such as The Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program that provides loan guarantees of up to 80% of project costs or $250 million (USDA-RD, 2015).

The Biomass Crop Assistance Program (BCAP), created by the 2008 Farm Bill and reauthorized with adjustments by the 2014 Farm Bill (U.S. Farm Bill, 2008, 2014), also encourages biochar production. Although BCAP does not directly identify biochar, it offers funds to producers to sustain, harvest, and transport biomass crops. The Natural Resources Conservation Service (NRCS) in the United States Department of Agriculture (USDA) explicitly mentions biochar as a soil amendment to enhance soil carbon and improve the physical, chemical, and biological properties of the soil (USDA NRCS, 2019). Under this interim conservation practice, farmers in some states, including California, can use financial and technical help for applying biochar to their soils.

In sum, there have been a few policies and regulations that explicitly promote using biochar for sustainable agriculture. If efficacy is shown in field trials with biochar produced from orchard biomass in California's Central Valley, we posit that the scale of these projects may quickly expand. In fact, once economic parameters are established as our study aims to do, this may accelerate biochar production and field trials. Hence, a market, and bioeconomy, for biochar produced from orchard waste in California could be created in a stepwise manner.

3. Materials and methods

3.1. Excel-based biochar enterprise budget tool

As follows is a summary of the itemized biochar production costs and assumptions used to develop the biochar enterprise budget presented as Supplementary Material. These values are incorporated in a baseline budget imputed into the regional economic model and used in a Monte Carlo simulation that considers production uncertainty.

The biochar production process includes various stages such as preprocessing, pyrolysis, storage, and transportation. An Excel-based enterprise budget provided as Supplementary Material accounts for costs associated with each production stage. The enterprise budget costs are specific to the Central Valley, California case study; however, the budget has been developed in a spreadsheet format with different drop-down lists to enable users to make modifications based on different projects elsewhere.

The spreadsheet is divided into two main categories: fixed and variable costs. As shown in Table 1, fixed biochar production costs include costs of the mobile pyrolysis unit, preprocessing equipment, pyrolysis setup, transportation, water tank, and storage facility among others. The variable costs include fuel, oil and lubricants, labor, and miscellaneous costs. Data collection for enterprise budget development is mainly based on local retailers, literature, and industry partners. To reduce bias and improbable assumptions, data triangulation was adopted, wherein the chosen prices are compared with other similar biochar production projects. All values are expressed in U.S. Dollars (USD).

Capital costs are simply expenses associated with fixed inputs used for biochar production. The truck selected for use is a 2020 Chevrolet Silverado 3500HD with a cost of $62,775 (General Motors, 2020).

After considering depreciation, insurance, interest, repairs, taxes, and insurance (DIRTI-5) and annual use over 10 years, the fixed cost of the truck each year equals $11,474.73. Moreover, trailers are essential

Table 1
Biochar production enterprise budget baseline, Central Valley, California. All production costs associated with biochar production assume 1 Mg day^{-1} production rate and no stochasticity.

Items		
Fixed Costs	**Per Unit Cost, USD**	**$ Mg^{-1}**
Truck	$62,775	$46.84
Trailer and fabrication	$30,000	$25.21
Chainsaw	$1,929.95	$4.44
Horizontal Grinder	$259,400	$255.87
Utility Tractor	$113,669	$126.04
Mobile Pyrolysis Unit	$250,000	$202.72
Biochar Bagging Equipment	$47,145.13	$35.73
Storage Shed	$49,121	$32.33
Portable Toilet	$1,277.35	$0.84
Portable Septic Tank	$500	$0.33
Fees, Permits, and Other Payments		$24.34
	Total fixed costs	$754.68
Variable Costs		
Fuel		
Truck		$1.47
Horizontal Grinder		$197.22
Utility Tractor		$61.63
Biochar Bagging Equipment		$9.86
Chainsaw		$4.94
Oil and Lubricants		
Chainsaw		$1.82
Horizontal Grinder		$72.58
Utility Tractor		$22.68
Biochar Bagging Equipment		$3.63
Labor		
Pre-processing		$127.84
Operations and Transportation		$144.88
Miscellaneous		
Biochar Bags		$45.79
Waste Disposal		$23.42
	Total variable costs	$717.76
Administration fees		$69.72
Total Fixed and Variable Costs		$1,542.16

and suitable for hauling oversized loads. These would be required in biochar production to aid with moving the pyrolysis unit. The price range for trailer and fabrication is $20,000 to $50,000 (Bonander Trailers, 2020).

A horizontal grinder will be used in case there is a need to grind feedstock into a smaller size. The grinder used in this project is Morbark 2230 horizontal grinder and the price is $259,400 (Alexander Equipment, 2020).

The chainsaw and utility tractor are important machinery required for feedstock preprocessing. The John Deere 5125R utility tractor and 540R loader are valued at $102,818 and $9,862 (Deere and Company, 2020). We chose the Frontier AP12F Fixed Pallet Forks, valued at $989 (Mutton Power Equipment, 2020) because it is compatible with John Deere tractors. The MAGNUM® 25-inch bar MS 880 chainsaw, valued at $1,929.95, was selected for processing tree logs (Winton Hardware, 2020).

The cost of the pilot mobile pyrolysis unit ranges from $250,000 to $300,000, comprising the largest equipment cost in the budget.

Biochar will be bagged after production by the Rotochopper Go-Bagger 250, valued at $47,145.13 (Rotochopper Inc, 2020). Until there is sufficient biochar demand that would allow transportation by truckload, bagging biochar is a conservative strategy to cultivate multiple distribution channels. This cost may eventually be eliminated once markets develop.

Given that pyrolysis would be conducted with a mobile unit, supplemental facilities for both workers and biochar management are recommended. These include a storage shed, portable toilet, and portable septic tank. The storage shed is required to store biochar between production and sale. The total cost for these items equals $50,898.35 (All Safety Products, 2020a, 2020b; Buildings Guide, 2019).

All businesses must obtain a business license before carrying out business transactions. The estimated range for a California Business License Fee is $50 to$100 for a small business license (Corporation Service Company, 2020), with a $100 business license fee selected for this project. Businesses with employees must maintain workers' compensation insurance coverage on either a self-insured basis, through a commercial carrier, or the state workers' compensation insurance fund. The average cost equals $7.71 of $100 per employee (or 7.71% of payroll). Additional fees for water and sewage come from the City of Chowchilla in the Central Valley (Chowchilla, 2020). Water and sewage cost $47.82 and $19.02 per month, assumed as constant rates throughout the life of the project.

Operating costs consist of fuel, oil, and lubricant costs for all the machinery.

Fuel costs include diesel and gasoline costs. The costs and consumption vary greatly based on project needs. The baseline cost is calculated based on the assumed distance traveled each day and fuel consumption. The range value for diesel is within $0.79–$1.03 L^{-1}. For gasoline, the range is $0.69–$1.05 L^{-1} (U.S. Energy Information Administration, 2021).

To estimate the diesel consumption for the horizontal grinder, utility tractor, and biochar bagger, we multiplied the liter per hour fuel consumption rate by fuel price per liter (Brinker et al., 2002). Based on the literature, we assume hourly fuel consumption in liters for each diesel machine is 0.19 multiplied by kilowatts of each type of equipment (Miyata, 1980).

The horizontal grinder, utility tractor, and biochar bagger have 298.3, 93.2, and 14.9-kilowatt engines.

Labor operation costs are estimated at a rate of one person for preprocessing and one person for operations and transportation. The hourly salary range for agricultural machinery operators in California equals $15 to $20 (CalCareers, 2020).

3.2. Stochastic cost estimation and sensitivity analysis

Biochar production with a mobile pyrolysis unit is a relatively new technology, with numerous production costs that may not be easily estimated. Most studies use deterministic cost estimation methods based on assumptions and available data (Ahmed et al., 2016; Kim et al., 2015), though this potentially neglects the inherent uncertainty of different biochar production pathways. Due to limited data on mobile pyrolysis units, some budget items were made stochastic to test the net effect on production costs. Probabilistic modeling and stochastic analysis are among the techniques that help to rigorously reduce epistemic uncertainty arising from the lack of empirical data.

To develop a realistic estimation of the biochar production costs and evaluate the effect of uncertainty, a Monte Carlo (MC) simulation is used to capture changes in input values on final estimated biochar costs. The MC technique iteratively estimates the production output given a set of deterministic and random inputs. The MC simulation samples from a designated probability distribution at the start of each iteration and performs forward modeling to generate an output distribution. Input distributions are defined with the help of historical project information and are expected to fit the available data (Connor and MacDonell, 2005).

The max, mean, and min biochar production costs are calculated through a stochastic analysis using @Risk software from Palisade Corporation (Palisade, 2019).

The MC simulation uses the following steps:

1. Select the parameters assumed to be stochastic.
2. Based on the literature and available information, develop an appropriate distribution for each parameter using a triangular and PERT distribution, assuming min, mode, and max values, if known.
3. Form a forward model. The forward model (a mapping) assumes all the values are deterministic and estimates the output of a mapping given a specific set of inputs. The forward model in this study comes from the enterprise budget described in Section 3.1 and provided as Supplementary Material.
4. Once a distribution for each stochastic parameter and the forward model are developed, the MC iterates over randomly chosen values for each parameter from the corresponding distribution and performs a forward analysis.
5. Assuming that n iterations are performed, for each iteration, one value for uncertain parameters are chosen from the corresponding distributions. Using the developed enterprise budget, for each given value and the rest of the values that are already determined (deterministic values), final costs are calculated.
6. Finally, the ensemble of final costs from each iteration is plotted to generate a distribution of the final cost.

A sensitivity analysis is also performed for each case to determine the most sensitive parameters affecting the total cost of biochar production. The effect of a per unit increases in fuel, permit, labor costs, and production rates on final production costs are evaluated.

3.3. Break-even analysis

Break-even price analysis informs producers of the price necessary to attain profitability given a particular output, which helps with marketing decision (Dillon, 1993). We conduct a break-even price analysis of production and sales output needed for biochar producers to recover their costs.

3.4. Regional economic impacts of biochar production

Direct, indirect, and induced economic impacts of biochar production in a 9-county region of California's Central Valley are estimated using IMPAN software (IMPLAN, 2021), an input-output model originally developed by the U.S. Forest Service (Olson and Lindall, 1996; Steinback, 1999) that considers inflationary or deflationary effects over time (Joshi et al., 2012). Regional economic impacts are estimated based upon the upper and lower bounds of the 90% confidence interval for

Mg^{-1} total cost estimates and four ranges of biochar production rates. Cost estimates from our baseline analysis are entered into the input-output model, rather than commercial revenues, to demonstrate potential economic contribution of just adding the cost of biochar production as an alternative to burning orchard crop residues. That is, spending on biochar production will create ripples of value through the local economy, where burning contributes nothing. The full value of biochar in a future analysis (beyond of the scope of this paper) would include sales that have yet to be developed, health benefits through reduced air pollution, and reduced carbon emissions that have not yet been counted.

4. Results and discussion

Table 1 shows a summary of fixed and variable biochar production costs for the baseline scenario, equal to $754.68 and $717.76 Mg^{-1} of biochar. These costs are calculated without considering the uncertainty, or stochasticity, in parameters.

Capital costs, which mainly include machinery costs, will not change with biochar production volume. In this project, it is assumed that all the machines will be financed for ten years with an interest rate of 10%. Insurance is calculated at 1% of the purchase price and taxes 8.25% of the purchase price. Variable costs are mostly fuel and labor expenses that directly change with the amount of biochar production. We assume 8 h day^{-1} work for transportation and operation for 261 days a year. The preprocessing machines run for 4 h day^{-1}. While biomass residues are assumed to be available from nearby farms free of charge, we include feedstock transportation costs in the budget. For the baseline scenario, it is assumed that the biochar production rate is 1 Mg day^{-1} (Wrobel-Tobiszewska et al. 2015).

4.1. Stochastic analysis

The assumptions made in the biochar enterprise budget are subject to change under different circumstances. Fuel prices fluctuate based on changes in demand or supply. Permit costs also vary depending on the location of the project and existing policies. Moreover, investigation and preparation fees cannot be accurately specified before the start of the project.

Labor cost is another important variable that can change by season, workload, and operation type. To account for these uncertainties, we analyze labor costs stochastically using a triangular distribution in @RISK software (Palisade, 2019). A triangular distribution has three parameters: the lower limit, the upper limit, and the mean. PERT distributions are considered a simplistic approach to turning the decision maker's viewpoints into parameter estimates (Stein and Keblis, 2009). The minimum, maximum, and most likely values for each parameter, summarized in Table 2, are based on historical data, expert opinions, literature, and project input from experimental biochar production equipment undergoing project testing. Fig. 1(a, b, c) shows the triangular distribution defined for each of the uncertain parameters (permit, fuel, and labor costs).

Biochar production rates are considered to have a major impact on the final cost. As shown in Table 2, production rates vary considerably

Table 2
Minimum, maximum, and most likely values for each uncertain parameter to form a triangular distribution.

Triangular distribution parameters	$ Mg^{-1} produced biochar	Source
Permits	Min = $1.39, Mean = $13.67, Max = $29.59	(Chowchilla 2020; Governor's Office of Business and Economic Development 2020; Keske et al. 2018)
Fuel	Min = $13.31, Mean = $83.33, Max = $148.29	(U.S. Energy Information Administration, 2021; U.S. Department of Energy, 2020; Brinker et al., 2002; Miyata, 1980)
Labor	Min = $31.37, Mean = $103.34, Max = $197.6	(CalCareers, 2020; Keske et al. 2018)

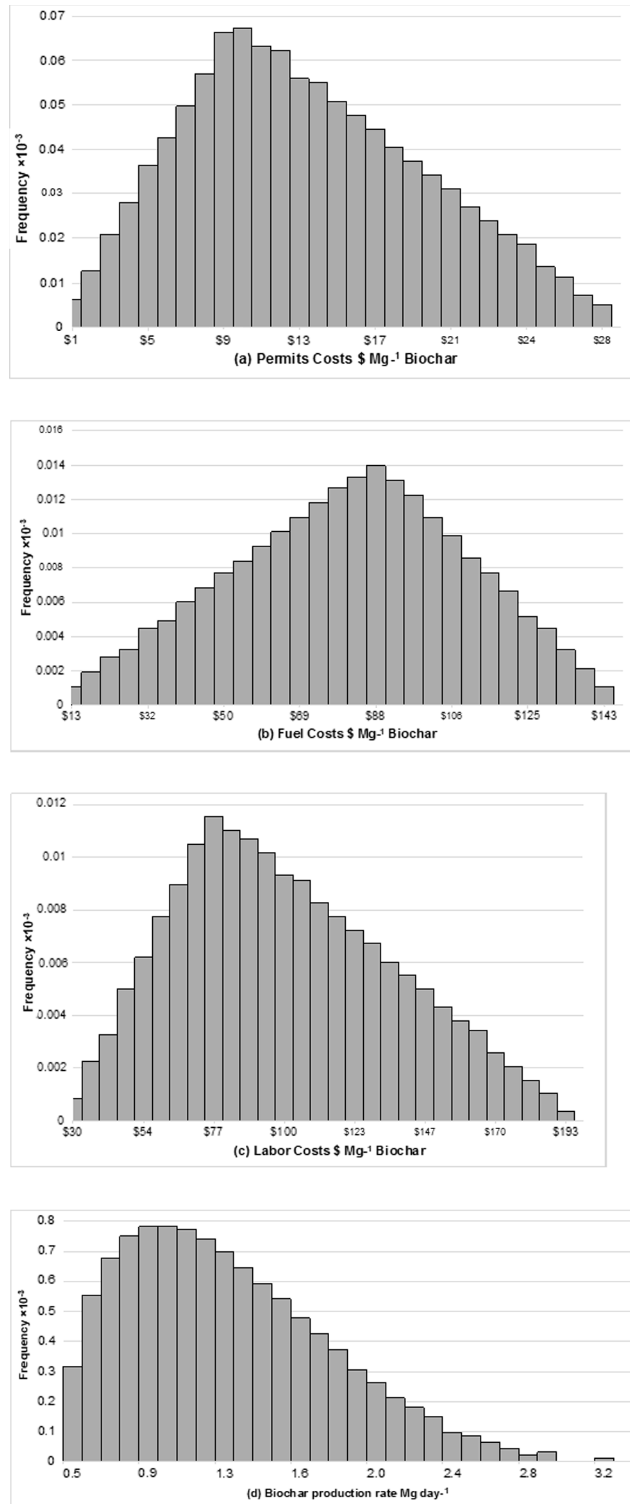

Fig. 1. Probability distributions for uncertain inputs. Graphs a, b, and c show the triangular distribution defined for each of the uncertain parameters (permit, fuel, and labor costs). The mean costs of the permit, fuel, and labor per metric ton biochar are $13.67, $83.33, and $103.34. Graph d utilizes a PERT distribution.

based on different production conditions such as feedstock type and pyrolysis unit properties. Kim et al. (2015) show that the productivity of their BSI pyrolysis system, which was used to produce biochar from sawmill residues, was 0.156 tons per hour. With an average of 7.6 h of work day^{-1}, the mean biochar production amount was 1.19 Mg day^{-1}. Another biochar economic analysis estimated the CharMaker MPP20 mobile pyrolysis plant could produce 1 Mg of biochar after 4 h of operation (Wrobel-Tobiszewska et al., 2015). Keske et al. (2018) assumed approximately 2 Mg day^{-1} of operation of biochar could be produced from a mobile pyrolysis unit. Thengane et al. (2020) used a mobile in-woods torrefaction of forest residues to produce biochar and suggested that biochar yield can vary based on the air-biomass ratio and the residence time.

The mobile pyrolysis unit selected for our project is reported as a batch unit with a capacity of 16 cubic yards. However, based on the availability and type of feedstock and the time of production (winter or summer) the amount of biochar produced can be as low as 0.5 Mg day^{-1}. The best-case experimental scenario for our pilot biochar production can be as high as 3.5 Mg day^{-1}. To account for all the different production volumes, we consider a PERT distribution for this parameter instead of triangular distribution. A PERT distribution gives more weight to the mean value rather than maximum and minimum values (Petter and Tyner, 2014). The defined PERT distribution for biochar production rate per day is shown in Fig. 1(d). The values for defining max, mode, and min for a PERT distribution are presented in Table 3. The most cited value is approximately 1 Mg day^{-1}, therefore the mode set for PERT distribution equals 1 Mg day^{-1}. The max and min are defined based on our experimental pyrolysis unit, 0.5 and 3.5 Mg day^{-1}.

The resulting probability distribution of total biochar cost is presented in Fig. 2. This has been simulated from biochar production prices found in the literature and summarized in Table 4. The simulation results show that the production costs of using portable pyrolysis biochar unit ranges between $448.78 and $1,846.96 Mg^{-1} of biochar. The cost distribution is not symmetric and is skewed toward the lower limit. This shows that although the upper range is high, the most frequent costs are less than $1,000 Mg^{-1} of biochar and there is a 90% probability that biochar cost will be between $571 and $1,455 Mg^{-1}. The cumulative probabilities and low, mean, and high values of predicted biochar production costs are presented in Fig. 3. There is a less than 5% probability of biochar costs being less than $570. However, 50% of the result of the simulations indicate a final cost of less than $863 Mg^{-1}.

4.2. Sensitivity analysis

We conduct a sensitivity analysis to measure the sensitivity of final production costs to uncertain inputs (fuel, permit, labor costs, and production rate). The results of sensitivity analysis in Fig. 4 show the changes in the mean cost of biochar Mg^{-1} as each uncertain input varies over its range. For instance, when the biochar production rate varies, keeping all other values constant, the mean biochar cost Mg^{-1} is within $577.88 and $1,477.56. Similarly, for other parameters, the lower and upper range of the mean biochar cost Mg^{-1} is shown in Fig. 4.

The bars are shown in decreasing order of their lengths from top to bottom so that the inputs at the top are those with the largest effect on the mean production cost of biochar. The biochar production rate has the most impact on the final cost. By increasing the production volume, we can significantly lower the final cost of biochar. However, it may not be a feasible option unless the technology barriers of high-capacity portable units are resolved and that there is a substantial demand for biochar.

Other parameters that may affect the costs are labor and fuel expenses. In this study, we assumed that feedstock would be collected free of charge. However, tipping fees would be charged to cover transportation and preprocessing costs.

Table 3
Minimum, maximum, and mode values for production rate to define the PERT distribution.

Mean biochar rate (Mg day^{-1})*	Description	Source
1.19	BSI pyrolysis system	Kim et al. (2015)
1	CharMaker MPP20 mobile pyrolysis	Wrobel-Tobiszewska et al. (2015)
2	CharMaker MPP20 mobile pyrolysis plant (slow pyrolysis)	Keske et al. (2018)
1.56	Biochar Solutions mobile pyrolysis plant (slow pyrolysis)	Keske et al. (2018)
0.6	Biochar from woodchips using an integrated portable system	Eggink et al. (2018)
0.5–3.5	Pilot portable biochar unit	Experimental

* Assuming a rate of 6–8 h work day^{-1}.

4.3. Break-even analysis

Break-even analysis conducted at four production outputs (0.5, 1, 2, 3.5 Mg day^{-1}) would yield 130.5, 261, 522, and 913.5 Mg year^{-1}. Break-even analysis for the baseline scenario for one year assuming a midline production rate based upon Wrobel-Tobiszewska et al. (2015) of 1 Mg day^{-1} (261 Mg year^{-1}) biochar, shows that biochar prices cannot be less than $ 1,426.2 Mg^{-1}; otherwise, economic loss occurs. Not surprisingly, when production increases, break-even prices lower. Break-even prices for 2, and 3.5 Mg day^{-1} biochar production equal $1,071.96 and $920.16. These values, even with higher rates of biochar productivity rates, are substantially greater than the break-even prices reported by Shabangu et al. (2014), but on par with mobile pyrolysis break-even prices reported by Granatstein et al., (2009). However, results of our break-even analysis shows that profitability is feasible, with the typical biochar sales price reported by Groot et al. (2018). With some investment into biochar production, it follows that improvement in production efficiency, and market prices would be expected.

4.4. Regional economic impacts of biochar production by counties in Central Valley

Expenditure data from the upper and lower boundaries of the 90% cost intervals ($571 Mg day $^{-1}$ and $1,455 Mg day^{-1}) were derived in the stochastic analysis presented in Section 4.1. These costs, along with four different biochar production levels (0.05, 1, 2, and 3.5 Mg day^{-1}) summarized in Table 3, were entered into the IMPLAN along with the budget code categories provided in Section 3.1. Estimates of regional economic impacts from biochar production in 9 Central Valley counties responsible for most of the state's almond production are shown in Table 5.

Not surprisingly, new job creation (18) and direct impacts, calculated as changes that occur in the relevant industry from overall final demand changes (Schmit et al., 2013), both increase when there is simply private or public investment into biochar production. Naturally, total economic output rises with higher production rates and cost levels ($670,639.50 at the lowest cost and production rate to $11,962,282.50 at the highest production and cost rates).

The Social Accounting Matrix (SAM) multipliers – computed as a ratio of total impacts to direct impacts, are all greater than one suggesting that a unit dollar worth of investing in the biochar industry would result in more than a dollar value-added economic returns across all economic indicators.

The investment into biochar production as an alternative to crop residue burning also offers increases in indirect impacts (changes in inter-industry purchases in response to new demands from the directly affected industries) and induced impacts, the sales, income, and employment values resulting from expenditures by workers from direct and indirect sectors (Steinback, 1999). The induced (ripple effect) impacts emanate from different economic sectors mainly due to changes in

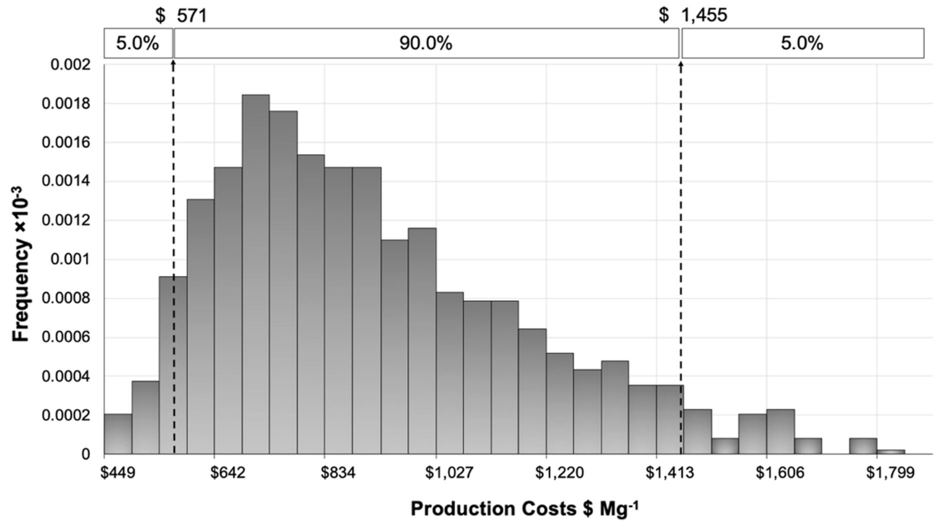

Fig. 2. Probability density histogram for total biochar cost per metric ton over production volume and permits, fuel, and labor costs.

Table 4
Biochar Prices Reported in Literature.

Biochar Price Mg^{-1}	Description	Source
$1,044	Minimum selling price of biochar	Sahoo et al. (2019)
$220–$280	Break-even prices	Shabangu et al. (2014)
$1,600	Most commonly cited sale prices	Groot et al. (2018)
$1,742–$2,077	Mobile pyrolysis break-even price	Granatstein et al. (2009)
$899–$2,778 (mean $1,834)	Reported industry wholesale price	Campbell et al. (2018)

household spending patterns (Miller and Blair, 2009, Perez-Verdin et al., 2008).

The indirect and induced expenditures indicate clear economic benefits in addition to the direct economic expenditures into biochar production. In other words, producing biochar as a management alternative to openly burning orchard crop residues creates additional economic development in the 9-county study region that is also considered an underserved area of the state.

4.5. An economic opportunity to create a bioeconomy

This study reviews the costs of biochar production but doesn't address the hard to define benefits such as sales revenue, health, or carbon sequestration. A farmer might consider biochar production as adding a cost to their farm, and it would be. Our analysis and previous study findings cannot assure farmers or biochar producers that they would be able to sell their product at a profit. However, as with any new technology, we expect costs will decline and markets will expand, eventually making biochar a profitable venture. In addition, society has a stake in the success of this market in that air pollution will be reduced and carbon will be sequestered. While the value of reducing air pollution is unknown, there is a pecuniary benefit generated by biochar production that might justify a social investment to help farmers kickstart this market. A case could be made for underwriting a biochar production program to farmers on a pilot basis as an alternative to crop residue burning.

The costs to adopt biochar are shown as the direct cost of output in Table 5. For example, for the $1,455 Mg^{-1} scenario, at a conservative

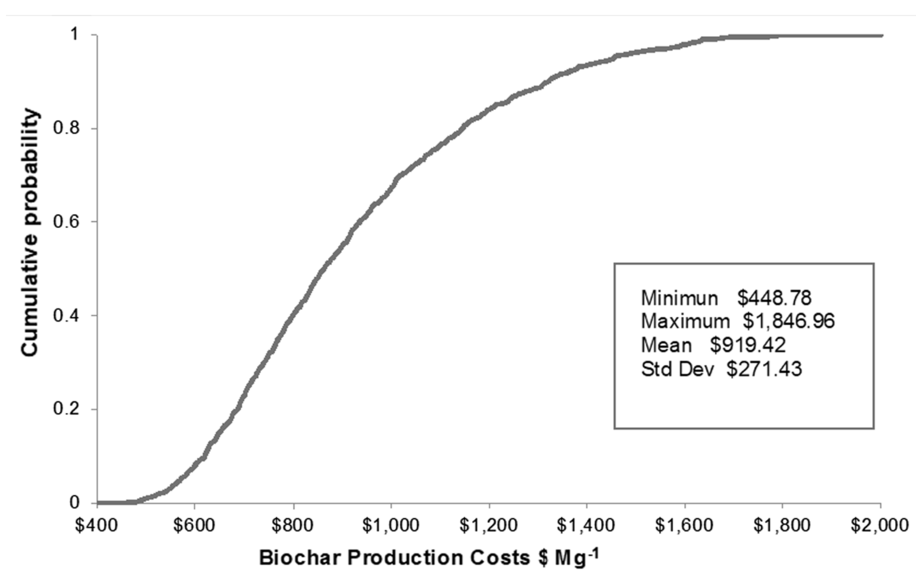

Fig. 3. Cumulative density function showing total biochar cost Mg^{-1} over production volume, permit, fuel, and labor costs.

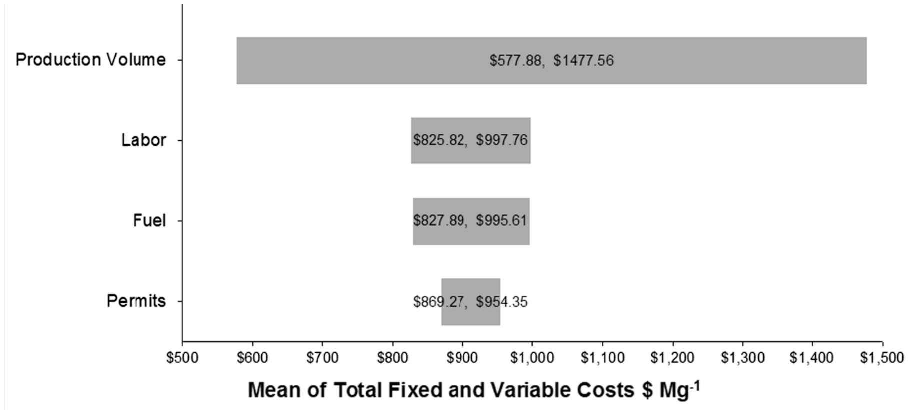

Fig.4. Effect of changes in permits, fuel, labor costs, and production volume on the mean cost of biochar. The numbers in each bar show the lower and upper range of the mean biochar cost Mg^{-1}.

Table 5
Regional Economic Impacts of Biochar Production in Central Valley, California.

(1) Combination	(2) Activity	(3) Direct Impacts	(4) Indirect Impacts	(5) Induced Impacts	(6) Total Impacts	(7) Total SAM Multiplier
$571 Mg^{-1} and production rate of 0.5 Mg day^{-1}						
	Employment	18.00	10.64	3.62	32.26	1.92
	Labor income ($)	645,015.32	535,010.16	172,580.33	1,352,605.80	2.10
	Total value added ($)	828,737.25	795,837.16	340,098.43	1,964,672.84	2.37
	Output ($)	670,639.50	1,602,814.75	563,071.55	2,836,525.80	4.22
$571 Mg^{-1} and production rate of 1.0 Mg day^{-1}						
	Employment	18.00	12.40	4.04	34.44	1.91
	Labor income ($)	688,686.63	619,248.24	192,429.54	1,500,364.41	2.18
	Total value added ($)	1,056,130.50	917,278.85	379,328.31	2,352,737.66	2.23
	Output ($)	1,341,279.00	1,848,426.33	628,005.81	3,817,711.13	2.85
$571 Mg^{-1} and production rate of 2.0 Mg day^{-1}						
	Employment	18.00	15.92	4.88	38.80	2.16
	Labor income ($)	776,029.26	787,724.40	232,127.96	1,795,881.62	2.31
	Total value added ($)	1,510,917.01	1,160,162.23	457,788.06	3,128,867.30	2.07
	Output ($)	2,682,558.00	2,339,649.48	757,874.31	5,780,081.79	2.15
$571 Mg^{-1} and production rate of 3.5 Mg day^{-1}						
	Employment	18.00	21.20	6.14	45.33	2.52
	Labor income ($)	907,043.21	1,040,438.64	291,675.59	2,239,157.44	2.47
	Total value added ($)	2,193,096.76	1,524,487.31	575,477.69	4,293,061.76	1.96
	Output ($)	4,694,476.50	3,076,484.22	952,677.06	8,723,637.78	1.86
$1,455 Mg^{-1} and production rate of 0.5 Mg day^{-1}						
	Employment	18.00	13.36	4.27	35.63	1.98
	Labor income ($)	712,625.55	665,424.28	203,310.10	1,581,359.93	2.22
	Total value added ($)	1,180,778.64	983,848.46	400,832.60	2,565,459.71	2.17
	Output ($)	1,708,897.50	1,983,061.05	663,600.24	4,355,558.78	2.55
$1,455$Mg^{-1}$ and production rate of 1.0 Mg day^{-1}						
	Employment	18.00	17.85	5.34	41.19	2.29
	Labor income ($)	823,907.10	880,076.48	253,889.09	1,957,872.67	2.38
	Total value added ($)	1,760,213.29	1,293,301.46	500,796.65	3,554,311.39	2.02
	Output ($)	3,417,795.00	2,608,918.92	829,063.17	6,855,777.09	2.01
$1,455$Mg^{-1}$ and production rate of 2.0 $Mgday^{-1}$						
	Employment	18.00	26.82	7.47	52.29	2.91
	Labor income ($)	1,046,470.20	1,309,380.89	355,047.06	2,710,898.14	2.59
	Total value added ($)	2,919,082.57	1,912,207.45	700,724.75	5,532,014.77	1.90
	Output ($)	6,835,590.00	3,860,634.66	1,159,989.04	11,856,213.70	1.73
$1,455$Mg^{-1}$ and production rate of 3.5 Mg day^{-1}						
	Employment	18.00	40.28	10.68	68.95	3.83
	Labor income ($)	1,380,314.84	1,953,337.49	506,784.02	3,840,436.35	2.78
	Total value added ($)	4,657,386.50	2,840,566.44	1,000,616.89	8,498,569.84	1.82
	Output ($)	11,962,282.5	5,738,208.28	1,656,377.85	19,356,868.63	1.62

0.5 Mg day^{-1} production rate, the cost for farmers to adopt biochar would be about \$1.71 million. This investment by farmers ripples through the economy, generating indirect and induced returns. The value-added generated by their investment is about \$2.57 million. Therefore, subsidizing the full cost of \$1.71 million for farmers to invest in biochar would generate about \$2.57 million in value-added. The pecuniary gains (\$2.57 million – \$1.71 million) are positive. This justifies the financial investment, at least in the short run. Additional benefits will accrue through reduced pollution and carbon emissions. Said differently for clarity, if a subsidy was offered, biochar production would cost farmers either nothing, or very little depending on the size of the subsidy. The citizens that financed the subsidy would receive net pecuniary gain and would arguably receive more in environmental benefits than what they spent on the subsidy. More importantly, investors would start from zero social cost, and receive the benefits biochar has to offer: health, carbon sequestration, and revenue from sales for the biochar producers.

5. Conclusions

Our goal was to determine how we might turn burning residues in orchards around to create a bioeconomy through biochar production. Our study delivers a stochastic analysis to reduce epistemic uncertainty arising from highly variable biochar production and nascent commercial sales. However, until crop yield efficacy is clearly demonstrated, it is unlikely that commercial scale markets will develop.

Management of crop residues, and specifically orchard waste, is a complex problem in the study region and across the world. Approximately 50% of crop residues are burned, though converting crop residues to biochar is a sustainable closed-loop approach to accommodate problems associated with waste management.

The enterprise budget and the stochastic cost estimations developed for biochar production in this study can provide the necessary information to mitigate risks in the biochar production phase both in the U.S. and other countries globally facing a crop residue problem. Our findings confirm our hypothesis that there should be a feasible range of costs for biochar production and these results provide a launch-pad for which biochar production can be feasibly achieved both in California and other countries facing biomass problems. The findings are plausible, and the standard deviation is not so high, which suggests less variability.

In this research, we proposed to use the produced biochar as a soil amendment to agricultural fields near the location of biochar production. However, the on-farm benefits, such as the potential to sell biochar so that farmers could increase yields have not been discussed. Admittedly, this is an important limitation of our study and could be an interesting research area for future studies. Most importantly, biochar production from agricultural waste can be an important step toward improving a global bioeconomy.

However, larger-scale research is needed to determine possible benefits and address potential social and environmental problems such as air pollution and global climate change.

Given our findings, as in Palansooriya et al. (2019), this study suggests that biochar production can be an economically beneficial endeavor that should be promoted in the Central Valley, California, and indeed globally if a global bioeconomy is to be achieved. At the state level, there is considerable opportunity to expand biochar production as an alternative management practice to crop residue burning. According to Kaffka et al. (2013), California generates at least 70 million tons of waste biomass per year and in 2009, the Central Valley's almonds and walnuts contributed about 199,000 and 496,000 dry tons of biomass waste each year. The authors note the higher value of production of almonds and walnuts as one of the leading factors toward biomass generation. Once biochar production has gained efficiency, there is considerable room for expansion. California has at least two million acres of trees and vine crops which produce substantial amounts of woody biomass from clipping.

Given the potential to expand biochar production, this study is relevant to policymakers across the world as it provides evidence to suggest that biochar production is economically feasible and has the potential to improve most economic indicators. Furthermore, we offer a way to incentivize biochar production through subsidizing costs, while recouping the costs of the subsidies through indirect and induced costs. That is, the farmer spends money on a new production link that creates a bioeconomy, the government offsets those costs with the indirect and induced costs that will fully make up for the cost of the subsidy, and both producers and society get all of the benefits of biochar at no cost and less risk. In other words, biochar can be produced at no net cost, and the net benefit will be positive. Once biochar producers show consistent profitability (with more predictable biochar market prices and biochar output), biochar production would eventually become a private sector investment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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