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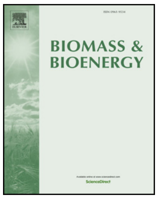

Research paper

Can biochar link forest restoration with commercial agriculture?

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ABSTRACT

The commercial use of low-value forest-origin biomass has long been considered for its potential to offset the cost of reducing wildfire hazard. The production of biochar simultaneously consumes low-value forest biomass and produces stable charcoal that, when applied to dryland agricultural soils, can increase water holding capacity and crop yield. In this way the production of forest-origin biochar has the potential to promote forest restoration, foster forest-related employment, increase agricultural competitiveness, and sequester carbon. Biochar offers the greatest opportunity where dryland food crops, limited water availability, existing energy transmission infrastructure, and high-fire hazard forests share the same landscape. In this paper we describe a landscape-level study based on this scenario to optimize wildfire hazard reduction treatments, biochar facility locations, and agroeconomic outcomes to evaluate the potential benefits needed to carry the costs of biochar production.

1. Introduction

The United States contains an estimated 80 million ha of federal and state forest and rangelands that face risk of large-scale wildfire and are in need of ecosystem restoration [1]. Programs to address wildfire risk reduction via mechanical thinning on national forests and other vulnerable lands typically cut substantial quantities of trees that have low value due to their small size and/or noncommercial species [2]. However, there are few strategies for the economical and environmentally-responsible use/disposal of low value trees. More often than not, harvested, low-value trees are burned on site, releasing the carbon they contain directly into the atmosphere. An alternative strategy is to convert the woody biomass from low value trees into biochar. Biochar is a carbon-rich byproduct of bioenergy production produced by slow pyrolysis or gasification. Because it is mostly carbon, biochar has been considered a promising way to sequester carbon [3–5] that is considered carbon neutral or negative (i.e. gains carbon) when coupled with sustainable production methodology.

The ability of biochar to improve soil quality and plant productivity has been extensively reviewed [4,6–8]. A recent meta-analysis [9] indicated that in nutrient-poor or acidic soils biochar, on average, increases crop yield by approximately 10%. Biochar mediates these improvements by increasing soil moisture retention, raising pH, increasing ion exchange capacities, improving water infiltration, providing nutrients, and adding labile carbon to highly-weathered soils [6]. However, the volumes of biochar required to effectively alter these soil properties are quite high (20–116 $\mathrm{Mg\,ha^{-1}}$) in comparison to other soil amendments [10]. The limited regional supply and high cost of biochar constrains growers' opportunities to apply biochar on subprime agricultural lands. Manipulation of agricultural soils will only be attractive if it is technically feasible over large areas, economically competitive with other approaches to offsetting greenhouse gas emissions, and environmentally beneficial. Although many are interested in producing biochar in small quantities for high value uses such as water filtration, production facilities capable of producing large ($> 10{,}000\ \mathrm{Mg\,yr^{-1}}$) quantities of biochar remain rare.

Biomass generated by forest restoration operations designed to reduce wildfire risk across forested landscapes can be used as inexpensive feedstock for bioenergy production plants. Unfortunately, delivery costs, energy production efficiencies, and concerns about carbon emissions often limit the market for biomass energy and the requisite wood residue feedstock. Other than in a few places with unique circumstances, the promise of inexpensive and renewable biomass energy has not come to fruition. However, newly emerging bioenergy and biochar production technology, when combined with markets for biochar for dryland agricultural soils, can increase food crop production

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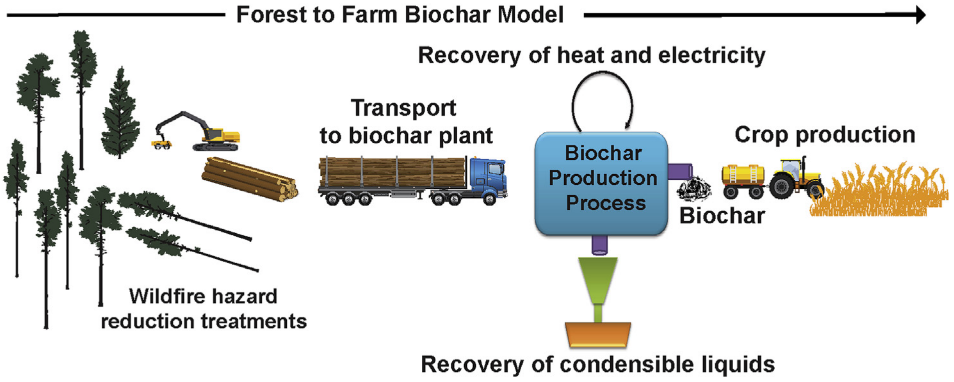

Fig. 1. Biochar supply chain from forest-to-farm.

while retaining the forest-origin carbon in stable soil pools. This would extend the established economic, social and ecological benefits from forest restoration [11–13] through to renewable energy production and ultimately increased food crop production (Fig. 1). Indeed, biochar offers the most significant potential opportunity where dryland food crops, limited water availability, green-energy delivery grids, and high fire-hazard forests are co-located within a regional landscape.

The focus of this paper, prepared by an interdisciplinary research team, is on biochar production operations and economics. We include an overview of a forest landscape biomass assessment in the Upper Klamath Basin in southern Oregon and northern California, USA to provide a feedstock supply cost curve as input to the economic analysis of biochar production. Our analysis then considers the total costs of producing biochar—including plant construction, capitalization, and operation—by two different biochar conversion technologies, four different biochar facility configuration scenarios, and two potential facility locations near the Oregon-California border. In addition, we evaluate agricultural sector markets for biochar in the study region.

The capture and re-use of energy and condensable by-products in the pyrolysis gases generated during biochar production have a significant influence on the plant's complexity and cost structure. We have evaluated how these plant design considerations influence the final production cost of biochar. A simple plant design scenario in which energy is purchased and all gases are flared has lower establishment costs but higher operating costs relative to plant designs that capture condensable by-products and thermal energy for drying, process heat, and/or electricity generation. The location of a plant relative to an existing wood products manufacturing facility also influences construction and operation costs. The biochar industry is rapidly evolving and cost estimates have primarily been based on bench tests or small production units. For the biochar production scale considered in this study, plant construction cost estimates at the Class 2 level [14] do not exist in the literature. We conclude with a discussion of the economic feasibility of pairing forest restoration and biochar production in the Upper Klamath Basin. Although our larger project evaluates non-monetized costs and benefits of biochar, including tracking forest carbon and potential benefits of carbon sequestration in agricultural use, this paper focuses on the direct economics of biochar production.

2. Methods

2.1. Biomass feedstock assessment

To estimate the supply chain costs of large-scale biochar production we studied the Upper Klamath Basin in southern Oregon and northern California (Fig. 2). About half of this 2.8 million ha basin is forested, and a large portion of the remainder is in pasture, dryland, and irrigated agriculture. The majority of the forestland in the Upper Klamath Basin is federally managed, with much of the forest susceptible to stand-replacing fire. To characterize and estimate the supply of biomass feedstock, we simulated forest restoration activities across the federal forestlands in the Basin using the BioSum analysis framework [15]. The objective was to identify and undertake a set of treatments that would elevate a composite fire resistance score [16,17] as much as possible. Treatments included thinning at different levels of residual stand density and thinning style, which would remove ladder fuels, diminish propagation of fire from surface to crowns, and separate tree crowns to reduce active crown fire. Costs of harvesting were estimated via equations developed during an operations study in the Klamath Basin [18,19] on the Fremont National Forest during 2016 using tethered harvesters and forwarders (Fig. 3).

We also evaluated delivery costs of feedstock, based on two potential biochar plant locations described below (see section 2.2.1): a brownfield site at Worden, OR, and a co-location opportunity with a sawmill in Yreka, CA.

2.2. Biochar plant design

An “engineering approach” was employed to estimate the economics of building and operating a large-scale biochar production facility at specific sites. This involved first defining the size, capabilities, core technologies, and operating schedule for the plant, and selecting specific locations where it would be built. The definition was refined by preparing process flow diagrams, mass and energy balance accounting, and general arrangement drawings for each of the 8 design scenarios [20]. These documents were then used to set performance specifications for specific process equipment to handle and convert the raw biomass into biochar, energy, and by-products. Equipment and technology suppliers were solicited to provide budget quotations. Motor lists were developed from these quotations to estimate total electricity requirements. The researchers worked with the plant site and primary technology cooperators to size the buildings, arrange the operations, and define the utility and infrastructure requirements for practical, successful operation of the plant. Staffing levels, purchased fuel, utility, maintenance and other operating cost estimates were generated from professional experience. All draft estimates have been vetted by experienced wood products manufacturing managers and engineers. An important tool employed to examine the economics of the various design and operating scenarios was the “Biomass Enterprise Economics model” [21]. All values are reported as dry tons (Mg).

2.2.1. Plant definition

Biochar facilities are influenced by both economies of scale and feedstock availability. Berry and Sessions [22] evaluated biochar plant scales from 13,608 to 45,360 $\mathrm{Mg\,yr^{-1}}$ (dry tons) using a modular thermal pyrolysis technology in several regions of the Pacific Northwest, including Lakeview, OR, and concluded that plant scales less than 13,608 $\mathrm{Mg\,yr^{-1}}$ were more costly than a 45,360 $\mathrm{Mg\,yr^{-1}}$ facility due to

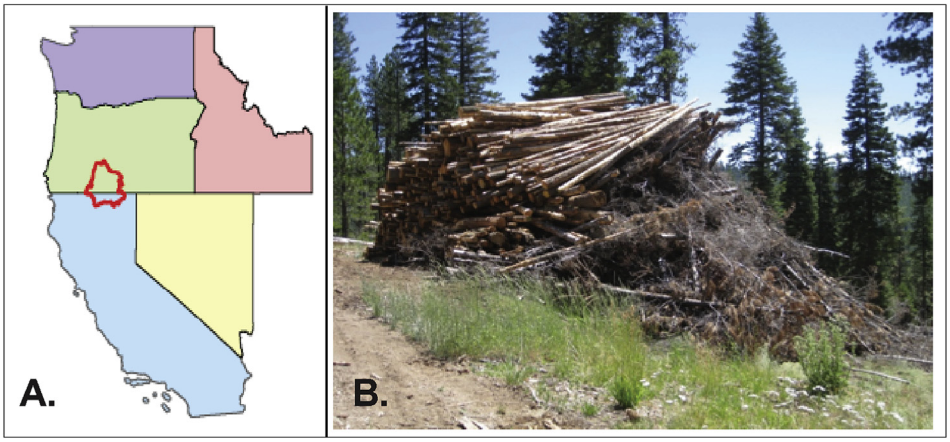

Fig. 2. A. Upper Klamath Basin (red outline) on border of Oregon and California, and B. forest residues, piled at roadside, that could be re-directed as biochar feedstock (right). Photo Credit: John Sessions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 3. Cable-assisted loaded forwarder moving uphill on a steep slope within a pilot test at Fremont National Forest, south-central, Oregon, July 2016. Photo Credit: John Sessions.

Table 1
Basic plant size design specifications.

Design Parameter	Specification
Annual feedstock capacity	45,360 Mg[a]
Feedstock moisture content	30% WBMC+, average at time of chipping
Feedstock form	defective and pulp logs of various lengths
Operating schedule	300 d y^{-1}, 22 h d^{-1}
Operating hours	6600 h y^{-1}
Design flow rate, dry wood	7257 kg h^{-1} (16,000 lb h^{-1})
Design flow rate, at 30% WBMC+	9818 kg h^{-1} (21,645 lb h^{-1})

[a] Dry Metric Ton; + Wet Basis Moisture Content.

both higher capital and operational costs per unit of biochar production. For this analysis, we assumed a facility with 45,360 Mg yr^{-1} capacity operating 6600 h per year with an average processing rate of 6.87 Mg of raw material (moisture free) per hour. (Table 1).

Two sites were chosen for evaluation. The first, owned by Green Diamond Resource Company, is a closed post and pole mill south of Klamath Falls in Worden, OR on Hwy 97 near the California border. The facility has not operated for several years but has some useable assets and is in a good location to receive material. It is located near a compost production facility that could plausibly enter into a fruitful partnership by blending biochar with compost for delivery to agricultural customers. The second, owned by Fruit Growers, Inc. is a small sawmill in Yreka, CA tooled to produce lumber for fruit crates and pallets from small diameter logs. Although this facility has excess sawdust that could supplement the feedstock supply, and some demand for process heat, only infrastructure advantages were considered in this analysis.

2.2.2. Biochar conversion technologies

We partnered with two biochar technology providers, the Karr Group (USA) and BSEI (China) to evaluate the costs of implementing similar sized plants in the Upper Klamath Basin. The Karr Group operates a demonstration facility featuring its “Karrbonator” technology in Onalaska, WA. They use a series of continuous tube & shell reactors to convert wood at 20% wet basis moisture content (wbmc) to biochar. The raw wood material, in small particle form, is continuously metered through the reactors by auger. Pyrolysis gases are drawn off the reactors by an ID fan. In their preferred configuration, the gases are condensed for vinegar and tar recovery, then the non-condensable gases are fired to heat the reactors indirectly or are flared to the atmosphere. BSEI operates a demonstration pilot plant of its “microwave” technology in Mangshi, Yunnan Province, China. This technology uses batch reactors to convert pre-dried biomass into biochar. Each reactor holds about 37.6 m^3 of wood as either chips or small particles. Processing time is 120 min per batch. Pyrolysis gases are drawn off the reactors through condensers to collect wood vinegar and tar. The non-condensable gases can be flared or sent to an energy recovery system.

Samples of woody biomass collected from our study site were submitted to both KARR and BSEI for conversion to biochar in their pilot plants. Yields were calculated, and the resultant biochar returned for further study and analysis. Although the experimental yields were somewhat lower than expected, both technology partners requested we base our economic calculations on the higher values referenced in Table 2. They are using those yields (KARR = 36%, BSEI = 37%) in their sales contracts, so are confident they can be achieved in commercial-scale installations using similar feedstocks.

2.2.3. Facility configuration scenarios

The technologies designed by our partners are compatible with fully utilizing the potential for condensable by-products and energy associated with the primary production of biochar. While full utilization of energy reduces air emissions and purchased energy requirements, it adds cost and complexity to the process. We explored four configuration scenarios to determine if added cost and complexity is justified (Table 3).

2.2.4. Key material flows

The most practical way to connect forest restoration operations with biochar production in the steep terrain of the Klamath Basin is by collecting small diameter logs as part of an integrated fuel treatment that also harvests merchantable timber, and delivers them by log truck to the biochar plant site (Fig. 4). Small diameter, non-commercial species and cull logs are received in a log yard, chipped (without

Table 2
Feedstock conversion process to biochar with assumptions for microwave (BSEI) technology or thermal pyrolysis (Karr) plant operation.

Step	Process	Assumption
Step 1	**Log yard, raw material receiving and storage**	
	Log dimensions	10–50 cm diameter, 2.4–7.3 m long
	Log truck deliveries	100 d yr^{-1}
Step 2	**Log reclaim to chipper, bark on**	
	Chipper operations	1720 h yr^{-1}
	Green tons logs/h	41.5
Step 3	**Chip storage capacity**	4 days
Step 4	**Dryer**	
	Evaporative loads, design	2495 kg (5500 lb) water h^{-1} to 8% $wbmc^{+}$ (BSEI) 1315 kg (2900 lb) water h^{-1} to 20% $wbmc^{+}$ (Karr)
	Dryer heat load	8.7 GJ h^{-1} to 8%, 4.5 GJ h^{-1} to 20%
Step 5	**Feed to hammermill**	
	Dried chips to hammermill	7500 (8%) or 8600 (20%) kg h^{-1}
	Hammermill target size	5 mm minus
Step 6	**Biochar reactor**	
	Biochar yield	37% (BSEI), 36% (Karr)
	Energy content of pyrolysis gas	58.9 GJ h^{-1} (BSEI), 60.9 GJ h^{-1} (Karr)
	Reactor energy input, BSEI	3.6 MW electric
	Reactor thermal energy input, Karr	15.8 GJ h^{-1}
Step 7	**Cooling water to reactor**	
	Biochar temp, in/out cooler	425/45 °C
	Biochar cooling load, design	0.85 GJ h^{-1}
	Cooling water temp, assumed	7 °C
	Cooling water flow, design	100 l min^{-1}
Step 8	**Biochar conditioning**	
	Exit cooler wbmc	6–12%
	Exit conditioning, wbmc	40%
	Water flow to conditioner	15 l min^{-1}
Step 9	**Biochar bagging**	
	Bagging station schedule	12 h d^{-1}
	Bag volume,	1.5 m^3
	Bag weight, full	410 kg
Step 10	**Warehouse and Shipping**	
	Bags filled per year	68,500
	Shipping schedule	8 h d^{-1}, 125 d yr^{-1}
	Warehouse capacity	15,000 bags

+WMBC; Wet basis moisture content.

debarking), dried, reduced in size with a hammermill, fed into the biochar reactor, cooled, and bagged for shipment in a 10-step process (Table 2).

Detailed mass and energy balances were prepared for each of the conversion technologies (thermal and microwave) and recovery scenarios, using our plant design assumptions and inputs from each of the technology partners. Detailed process flow diagrams and mass balances are available online [20].

2.3. Market analysis

We evaluated potential agricultural markets for biochar in the Klamath Basin by comparing the costs of production to the theoretical price farmers could afford to pay. To be financially attractive to a farmer, the combination of increased value of the crops plus the reduction in the costs of other inputs, such as irrigation, must exceed the cost of the biochar. If biochar benefits persist for a period of N years, the present value of an annual set of yield improvements to the farmer is:

$$\text{Present value of Net Yield Improvement} = \{\Delta V[(1+i)^N - 1]/[i\,(1+i)^N]$$

Where

V = Annual increased value of crop yield + reduction in other annual inputs, \$ ha^{-1} yr^{-1}
N = Persistence of biochar yield effect, years
i = Farmer's cost of capital, decimal percent

If T is the dry Mg equivalent of the biochar application, then the present value of the discounted yield improvements must be greater or equal to the cost of the biochar plus application costs.

$$\{\Delta V\,[(1+i)^N - 1]\ /[\,i\,(1+i)^N]\ \}/\,T \geq \text{Delivered Biochar Cost} + \text{Biochar Application Cost}$$

For example, if the net increase in annual value to the farmer for a 15 Mg application was \$2500 per ha with a persistence of 5 years, and the farmer's cost of capital was 8%, then the farmer could afford to spend a maximum of

$$\{\Delta V\,[(1+i)^N - 1]\,/\,[\,i\,(1+i)^N]\,\}/\ T = \$2500/\text{ha}\,[\,(1.08)^5 - 1]\,/\,[.08\,(1.08)^5]\,/\,15\text{ Mg} = \$665\text{ Mg}^{-1}$$

We evaluated the maximum price farmers could afford for biochar as a function of crop yield increases, for the six most common crops grown in Klamath County (potatoes, alfalfa, wheat, barley, oats, and hay). Crop values were estimated from county- and state-level surveys conducted by the USDA National Agricultural Statistical Services.

3. Results and discussion

3.1. Feedstock supply

The biomass assessment suggested up to 5.44 million Mg (bone dry) of biomass could be generated via forest restoration treatments in the study area over a 20-year period (Fig. 5). Combined collection and delivery cost to Worden, OR were estimated to range from \$43 to \$135 Mg^{-1} (Fig. 5) Like most of the dry forests in southeastern Oregon and northern California, the Klamath Basin lacks a pulp market, so small diameter, pulpwood sized logs, along with non-commercial

Table 3
Scenarios evaluated in terms of facility capabilities and complexity.

Location	Description
A	Worden, Oregon (possible co-location with compost facility)
B	Yreka, California (co-location with existing lumber mill)
Scenario	Description
1	*No energy or condensable by-product recovery*. All pyrolysis gases are flared to atmosphere, and all fuels and electricity required to drive the process are purchased.
2	*Heat recovery*. All pyrolysis gases are burned in a heat-recovery furnace. Thermal energy is recovered to heat the biomass dryer and the thermal pyrolysis (Karr) reactor. Excess heat is vented to atmosphere.
3	*Heat recovery plus power*. A thermal oil heater and ORC power recovery system is added after the heat-recovery furnace to generate electricity and supply process thermal requirements.
4	*Condensable liquid recovery, plus heat, plus power*. A system of condensers is inserted ahead of the heat-recovery furnace to collect vinegar water and bio-oil prior to burning the remaining gases to generate process heat and power.

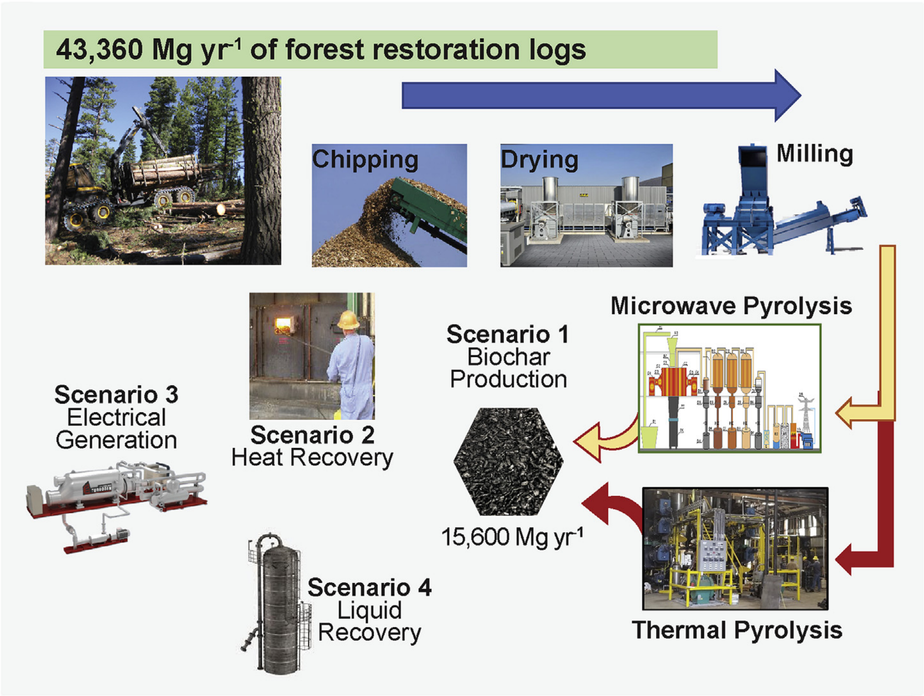

Fig. 4. Biochar plant process flow diagram with energy and byproduct recovery scenarios to convert 45,360 Mg of wood residues to more than 16,000 Mg y^{-1} of biochar. Photo credits: Clockwise top left to right: John Sessions, David Smith, Norris Thermal Technologies, Inc., West Salem Machine, BSEI, Inc., David Smith, Kristin Trippe, David Smith, Turboden, Inc., David Smith.

species and cull logs of all sizes, can be assumed available as biochar feedstock.

Full realization of biochar's benefits requires economical, high volume production at locations proximal to stable markets. Although we can only speculate on the implementation schedule for forest restoration on federal lands, we conservatively estimate that biomass could be available to support an annual feedstock supply of 45,360 Mg (dry ton) for 20 years (907,200 Mg total) at an average supply cost not exceeding \$55 Mg^{-1} (Fig. 5) to Worden, Oregon. Delivered cost to Yreka would be somewhat greater due to the greater transportation distance and California's lower permissible truck load sizes.

3.2. Biochar plant mass and energy balances

Input from technology partners and key vendors was used to prepare mass and energy balances (Table 4) for each of the four design scenarios (various levels of energy and by-product recovery) and the two primary pyrolysis technologies (microwave and thermal).

3.3. Emissions controls

In addition to the outputs described above, the plant emissions inventory is not expected to exceed "major source" limits for any criterion or hazardous pollutant. The design provides for clean combustion of all pyrolysis gases. Applying a softwood VOC emission factor of 0.45 kg Mg^{-1} to the low temperature, indirectly fired belt dryer (see Table 11.6.2–2 [23]) annual emissions are less than 21.8 Mg per year. NOx emissions are even lower (see Table 11.6.2–3 [23]). Therefore, no tailpipe controls are budgeted for the dryer. Particulate matter is controlled through extensive paving of the plant site, good housekeeping practices, and utilization of a negative air clean-up system with a bag house.

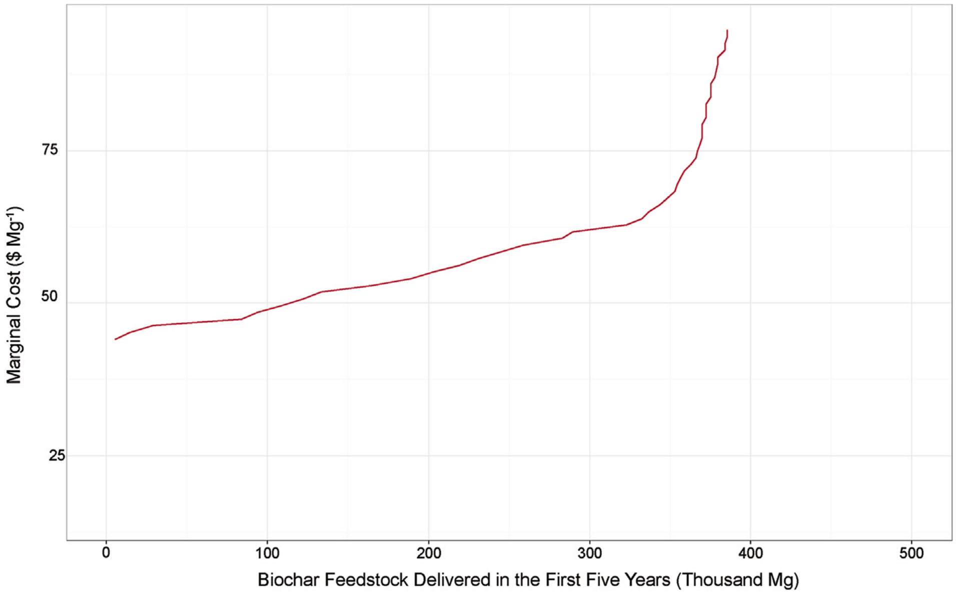

Fig. 5. Marginal cost (\$ Mg^{-1}) of collection and transport of forest residues from fuels treatments on the Upper Klamath Basin to a biochar facility in Worden, Oregon, for the first five years of facility operation. Costs include forwarding, loading, and haul. All treatments were assigned to the landscape assuming a 100-year average management return interval and an objective function maximizing Composite Resistance Score over a twenty-year planning horizon.

Table 4
Mass and energy balance by scenario and technology at average hourly production rate.

Scenario	Microwave Pyrolysis Reactor				Thermal Pyrolysis Reactor			
	1	2	3	4	1	2	3	4
Mass, wet kg h^{-1}								
Chips to reactor	7471	7471	7471	7471	8591	8591	8591	8591
Char out of reactor	2621	2621	2621	2621	2474	2474	2474	2474
Condensed vinegar & tar	0	0	0	598	0	0	0	1637
Remaining pyrolysis gas	4849	4849	4849	4251	5952	5952	5952	4480
Energy content, GJ h^{-1}								
Chips to reactor	130.2	130.2	130.2	130.2	130.2	130.2	130.2	130.2
Char fraction	71.0	71.0	71.0	71.0	69.1	69.1	69.1	69.1
Condensed vinegar & tar	0	0	0	5.2	0	0	0	8.8
Non-condensed gas	58.9	58.9	58.9	53.7	60.6	60.6	60.6	51.7
Losses (condense char water)	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5
Process heat, GJ h^{-1}								
Dryer demand	8.2	8.2	0[a]	0[a]	4.3	4.3	0[a]	0[a]
Reactor demand	0	0	0	0	15.8	15.8	15.8	15.8
1.6 MW ORC system input	0	0	34.8	34.8	0	0	34.2	34.8
Ambient losses	0	0	1.3	1.3	0	6.5	7.8	7.8
Excess heat vented	58.9	50.6	22.8	17.6	60.6	33.9	2.1	(6.8)

[a] Dryer heat supplied by Organic Rankine Cycle (ORC) system.

3.4. Capital estimate

The capital estimates to build the dedicated 45,360 Mg yr^{-1} biochar facility on the two selected plant sites with each of the four scenarios increases as the scenario becomes more complex (Table 5). The engineering approach utilized vendor quotes for supplying all the major pieces of process equipment. Unit costs were used to estimate costs for site preparation, buildings, roads and yards, structural steel and foundations, power distribution and controls, mechanical installation, engineering, general contractor services, and owner expenses. A contingency allowance of 15% is included in the total cost. With this level of specification and definition, the quality of the estimate is considered to be Class 2 by the Association for the Advancement of Cost Engineering with a target of being within 20% of the actual cost [14].

The totals for Scenario 1 in Table 5 are for constructing the basic plant on each of the two sites. The value of useable site assets is credited within the totals. This simple design does not allow for capture and reuse of energy from the pyrolysis gases but does employ a chip dryer and other process equipment operating on purchased fuels.

The cost of constructing the Scenario 2 plant increases with the addition of a combustion furnace, hot air ducting, and controls to serve the chip dryer, thermal pyrolysis reactor, and building heaters. In this scenario, a considerable amount of energy will still be vented to atmosphere after plant needs are met, especially if microwave technology is employed (Table 4).

Table 5
Capital estimates by site, pyrolysis technology, and design scenario ($ millions). Scenarios are described in Table 3.

Pyrolysis Platform	Microwave[a]	Thermal
Worden, OR		
Scenario 1	17.2	17.5
Scenario 2	18.8	19.1
Scenario 3	27.0	27.3
Scenario 4	27.8	28.1
Yreka, CA		
Scenario 1	17.0	17.3
Scenario 2	18.7	18.9
Scenario 3	26.9	27.1
Scenario 4	27.7	28.0

[a] The microwave technology provider, BSEI, advises that they expect the cost of the reactor and microwave generator to be significantly higher than reported here. Other indications are that the costs used to calculate these totals are reasonable. The values in Table 4, rather than those suggested by BSEI, were used for calculating operating cost items such as cost of capital and maintenance.

The Scenario 3 design adds a thermal oil heater to capture energy from the combustion furnace and heat a 5760 MJ (1.6 MWh) ORC (Organic Rankin Cycle) electric power generation system. This expensive equipment adds considerably to plant construction costs and operational complexity. The size of the ORC system was selected to use the remaining fuel energy in the pyrolysis gases after heating the thermal reactor. Its net output exceeds the thermal reactor plant average power demand but is not enough to keep up when the chipper is running. The microwave reactor requires considerably more power but less thermal energy, so a larger power generation system would be more appropriate than what is included in this design.

Under Scenario 4, the plant is reconfigured to capture condensable liquid byproducts from the pyrolysis gases prior to combustion. Doing so adds additional cost and considerable complexity to plant operations and reduces the amount of energy remaining for process use. This concept of liquids recovery is integral to both of our technology partner's process design. However, we are wary of the practicality of the concept due to poor experiences with handling condensable gases in other wood products facilities.

3.5. Operating costs

The cost of running the biochar plant, financing its construction, and selling the biochar product is a function of the plant operating schedule, staffing level, degree of operational complexity, raw material costs, purchased energy costs, various miscellaneous expenses, the cost of capital, and salvage value of the plant after its depreciated life.

The plant is scheduled to operate 300 days per year and produce biochar 7 days a week for 6600 productive hours. The plant wood yard receives and decks logs 5 days a week during dry weather months. The chipper operates 8 h per day, 5 days per week. Following biochar production and conditioning, the biochar is packaged in 1.5 m^3 super sacks. The bagging station runs 8 h per day, 7 days per week. Biochar shipments, by truck, occur seasonally, with a large product inventory being carried between shipping seasons.

The plant staffing level is the same for Scenarios 1 and 2 at both locations and using both primary technologies. Additional operations, maintenance, and supervisory staff are added for Scenarios 3 and 4 (Table 6) to deal with increased operational and plant complexity. The annual costs for hourly wages are based on prevailing industry rates for the region and include an overtime factor. Salaries are typical for the

Table 6
Biochar Plant Staffing (FTE) and annual payroll costs (\$). See Table 3 for descriptions of scenarios 1–4.

Position	Scenarios 1 & 2	Scenarios 3 & 4
Operator	5	6
Utility and laborer	11	11
Maintenance	4.5	5
Supervision	3	3
Management	3	4
Total Plant Staff (FTE)	26.5	29
Annual cost \$	1,743,000	1,873,200

FTE, Full Time Equivalent.

industry. A 40% benefit factor is applied to all positions.

Transportation costs impact the price of biomass feedstock across the two plant locations. The transportation costs to Yreka, CA are greater than to Worden, OR because the distance is greater and because the maximum truck weight permitted in California is 76% of the gross truck weight permitted in Oregon. Therefore, the Upper Klamath biomass assessment indicated that the cost of collection and delivery of biomass was estimated at \$55 Mg^{-1} to Worden, OR and \$66 Mg^{-1} to Yreka, CA.

The plant will need to purchase liquid fuels to operate rolling stock, electric power, and, in Scenario 1, natural gas to heat the dryer and thermal pyrolysis reactor. In the other scenarios, natural gas will be used as a start-up and pilot fuel. Some of the power costs are offset in Scenarios 3 and 4 due to the addition of the ORC power generator. In all cases, the energy requirements and costs for the microwave and thermal pyrolysis reactors are significantly different (Table 7). The assumed power supply scenario is that the plant will purchase electricity to meet all its requirements at a different rate than it sells ORC-generated power back to the utility.

Fuel consumption estimates were made for annual operation of all rolling stock for log and chip handling, warehouse and shipping, and site maintenance. The unit costs listed in Table 7 were then used to estimate annual plant energy costs (Table 8).

3.6. Cost of capital

The annual cost of capital depends on the facility cost, weighted cost of capital, facility life, facility salvage value, and annual production. Olson et al. [24] suggest an after-tax weighted average cost of capital of 8.3% based upon a study of investments in the power generation sector. Interest and depreciation can be calculated separately or combined based on the value to be depreciated plus the interest on the salvage value. We use the combined method, known as the Cost Recovery Annuity Method, recommended by the Agricultural and Applied Economics Association [25] calculating the average annual capital cost (AAC) as

$$\mathrm{AAC} = (\mathrm{P} - \mathrm{S})\{i\,[(1+i)^{\mathrm{N}}]\,/\,[\,(1+i)^{\mathrm{N}} - 1]\} + i\,S$$

Where

P = Plant construction cost, \$
S = Salvage value, \$
N = Life of Plant, years
i = Cost of capital, decimal percent

Table 7
Purchased and sold energy prices used in modeling.

Source	Price
Purchased diesel fuel (off road)	\$0.53 l^{-1}
Purchased natural gas	\$.0047 MJ^{-1}
Purchased electricity, Oregon	\$0.0250 MJ^{-1}
Purchased electricity, California	\$0.0375 MJ^{-1}
Sold electricity, to utility	0.0194 MJ^{-1}

Table 8
Annual energy costs (\$1000) of microwave or thermal pyrolysis plants, under four scenarios (see Table 3) located at two sites.

Scenario	Worden, Oregon				Yreka, California			
	1	2	3	4	1	2	3	4
Diesel	276	276	276	276	276	276	276	276
Natural Gas								
Microwave	264	8	8	8	264	8	8	8
Thermal	627	16	16	16	627	16	16	16
Electricity, net								
Microwave	2393	2484	1887	1911	3590	3648	3098	3134
Thermal	528	619	21	196	792	850	299	486
Total purchased energy								
Microwave	2933	2769	2171	2195	4130	3932	3381	3418
Thermal	1431	912	313	488	1694	1142	592	778

3.7. Total cost of producing biochar

The total cost of preparing biochar for shipment to markets is the sum of the delivered feedstock costs, the direct production costs associated with operating the plant as designed and described here, and the cost of capital, or financing costs, for constructing the plant. These costs have been calculated and compiled (Table 8) for each of the four construction scenarios, two technology systems, and two plant locations.

Table 9 reveals that the calculated overall cost of biochar production is minimized at \$474 Mg^{-1} with thermal energy recovery (Scenario 2) and the thermal pyrolysis technology at the Worden, OR site. The highest overall production costs of \$704 Mg^{-1} of dry biochar occur at the Yreka, CA site under Scenario 4 with microwave pyrolysis technology. This range of costs shows the impact of higher delivered raw material and electricity costs in California, coupled with microwave technology's high electricity usage. Our estimates of the costs associated with microwave technology would be significantly greater if the technology partner's (BSEI) revised pricing had been used in the model (see Table 5 note).

Scenario 3 (energy recovery for power generation) actually provides the lowest direct production costs (\$184 Mg^{-1}, dry biochar) due to reduced purchased energy costs. Indeed, when thermal pyrolysis is employed, the plant is nearly energy self-sufficient. However, when the extra cost of capital is added for the ORC power generation equipment, the overall production cost in Worden increases to \$500 Mg^{-1} of biochar. Still, it appears that power generation may be justified as it adds little to the plant's total annual operating costs.

The microwave pyrolysis technology provider, BSEI, points out that their system is designed to be operated only in Scenario 4 format. Their preferred strategy for energy recovery is to clean the pyrolysis gases through condensation recovery of liquids and filtering, then use the non-condensable fraction to fuel an internal combustion engine to generate electricity. The engine exhaust gases and cooling jacket water would be used for dryer heat. While this approach may well improve the attractiveness of microwave pyrolysis, it was not compatible with our scenario matrix, so was not evaluated.

The sensitivity of the total biochar production cost to changes in the seven most significant factors was evaluated by adjusting each cost +,-20% from the values in Tables 6, 8 and 9 for a plant constructed at Worden, Oregon. The analysis (Table 10), showed very high sensitivity to yield. This is logical, since the overall costs of production must be absorbed by the total volume of biochar available for sale. Higher yields increase the unit divisor, so reduce overall unit costs. Overall costs are the same if process yields are lower, so unit costs of biochar increase.

The sensitivity analysis also showed a strong relationship between purchased energy costs and the primary conversion technology

Table 9
Production costs per Mg of dry biochar produced under four scenarios (see Table 3) located at two sites at a product yield of 37% per Mg of feedstock input for microwave and 36% yield for thermal process.

Scenario	Worden, Oregon				Yreka, California			
	1	2	3	4	1	2	3	4
Direct biochar production cost, $ Mg^{-1}								
Microwave	321	312	290	292	392	381	362	365
Thermal	237	207	184	195	254	220	201	213
Direct biochar production cost, plus feedstock, $ Mg^{-1}								
Microwave	470	461	439	441	571	560	540	543
Thermal	390	359	337	348	438	405	385	397
Capital cost at 8% cost of capital, 20-year life, 20% salvage, $ Mg^{-1}								
Microwave	75	83	118	122	75	82	118	121
Thermal	78	86	123	127	78	85	122	126
Total Costs, including Feedstock, Production, and Capital, $ Mg^{-1}								
Microwave	545	543	558	563	646	642	658	665
Thermal	468	446	461	475	515	489	507	524
Annual Operating Costs, $Thousands yr^{-1}								
Microwave	9149	9119	9354	9447	10,836	10,775	11,043	11,161
Thermal	7657	7281	7516	7758	8412	7995	8278	8541

selected. Production costs using microwave technology are heavily influenced by the cost of purchased energy. The thermal conversion process is much less dependent on purchased energy costs, especially in those scenarios that offset internal energy demand through capture and reuse of pyrolysis gases. Other factors, such as cost of capital, labor, and feedstock, also have significant impacts.

3.8. Agricultural markets for biochar

Major crops in Klamath County include alfalfa, small grains (wheat, barley, and oats), hay from small grains and other grasses, and potatoes (Table 11). Aside from small amounts of vegetable production, alfalfa and potatoes are the highest value crops on an area basis. Accordingly,

Table 10
Impact on $ Mg^{-1} and % change of biochar cost by increasing or decreasing the seven most significant cost and yield factors by 20% for a plant built at Worden, Oregon. Delta Plus means an unfavorable 20% change in the factor would increase total cost and Delta Minus means a favorable 20% change in the factor would decrease total cost.

Microwave Scenario 1	Delta Plus	Delta Minus	Thermal Scenario 1	Delta Plus	Delta Minus
Biochar Yield	142 (25%)	−95 (−17%)	Biochar Yield	124 (25%)	−82 (−17%)
Purchased Energy	35 (6%)	−35 (−6%)	Feedstock Cost	31 (6%)	−31 (−6%)
Feedstock Cost	30 (5%)	−30 (−5%)	Plant Staffing Cost	21 (4%)	−21 (−4%)
Plant Staffing Cost	21 (4%)	−21 (−4%)	Plant Construction Cost	20 (4%)	−21 (−4%)
Plant Construction Cost	20 (4%)	−20 (−4%)	Purchased Energy	18 (4%)	−18 (−4%)
Discount Rate	13 (2%)	−13 (−2%)	Discount Rate	14 (3%)	−14 (−3%)
Plant Life	9 (2%)	−6 (−1%)	Plant Life	9 (2%)	−6 (−1%)
Microwave Scenario 2	Delta Plus	Delta Minus	**Thermal Scenario** 2	Delta Plus	Delta Minus
Biochar Yield	142 (25%)	−95 (−16%)	Biochar Yield	118 (25%)	−79 (−17%)
Purchased Energy	33 (6%)	−33 (−6%)	Feedstock Cost	31 (7%)	−31 (−7%)
Feedstock Cost	30 (5%)	−30 (−5%)	Plant Construction Cost	23 (5%)	−23 (−5%)
Plant Construction Cost	22 (4%)	−22 (−4%)	Plant Staffing Cost	21 (4%)	−21 (−4%)
Plant Staffing Cost	21 (4%)	−21 (−4%)	Discount Rate	15 (3%)	−15 (−3%)
Discount Rate	15 (3%)	−14 (−2%)	Purchased Energy	11 (2%)	−11 (−2%)
Plant Life	10 (2%)	−6 (−2%)	Plant Life	10 (2%)	−6 (−1%)
Microwave Scenario 3	Delta Plus	Delta Minus	**Thermal Scenario** 3	Delta Plus	Delta Minus
Biochar Yield	149 (25%)	−99 (−17%)	Biochar Yield	125 (25%)	−83 (−17%)
Feedstock Cost	30 (5%)	−30 (−5%)	Feedstock Cost	31 (6%)	−31 (−6%)
Purchased Energy	26 (4%)	−26 (−4%)	Plant Staffing Cost	23 (5%)	−23 (−5%)
Plant Staffing Cost	22 (4%)	−22 (−4%)	Plant Construction Cost	21 (4%)	−33 (7%)
Plant Construction Cost	22 (4%)	−32 (−5%)	Discount Rate	21 (4%)	−21 (−4%)
Discount Rate	21 (4%)	−20 (−3%)	Plant Life	15 (3%)	−9 (−2%)
Plant Life	14 (2%)	−9 (−2%)	Purchased Energy	4 (1%)	−4 (−1%)
Microwave Scenario 4	Delta Plus	Delta Minus	**Thermal Scenario 4**	Delta Plus	Delta Minus
Biochar Yield	151 (25%)	−100 (−17%)	Biochar Yield	129 (25%)	−86 (−17%)
Feedstock Cost	30 (5%)	−30 (−5%)	Feedstock Cost	31 (6%)	−31 (−6%)
Purchased Energy	26 (4%)	−26 (−4%)	Plant Staffing Cost	23 (4%)	−23 (−4%)
Plant Staffing Cost	22 (4%)	−22 (−4%)	Plant Construction Cost	16 (3%)	−34 (−7%)
Plant Construction Cost	17 (3%)	−33 (−5%)	Discount Rate	16 (3%)	−22 (−4%)
Discount Rate	17 (3%)	−21 (−3%)	Plant Life	15 (3%)	−10 (−2%)
Plant Life	14 (2%)	−10 (−2%)	Purchased Energy	6 (1%)	−6 (−1%)

Table 11
Top crops grown in Klamath County and value by land area and product mass.

Crop	Area Harvested[a] (ha)	Total Production[a] (Mg)	Value (\$ Mg^{-1})[b]	Value (\$ ha^{-1})
Oats	823	3167	\$207	\$795
Potatoes	3359	129,138[c]	\$160	\$6168
Barley	6635	33,086	\$124	\$618
Hay (excluding alfalfa and barley)	6798	34,347	\$190[d]	\$960[d]
Wheat	7274	32,790	\$136	\$615
Alfalfa	20,236	189,750	\$184	\$1722

[a] County-levels estimates from 2012 Census of Agriculture [20].
[b] Average statewide values from 2016 [21].
[c] County-level estimate from 2011 [19].
[d] Estimated value includes wheat and barley hay.

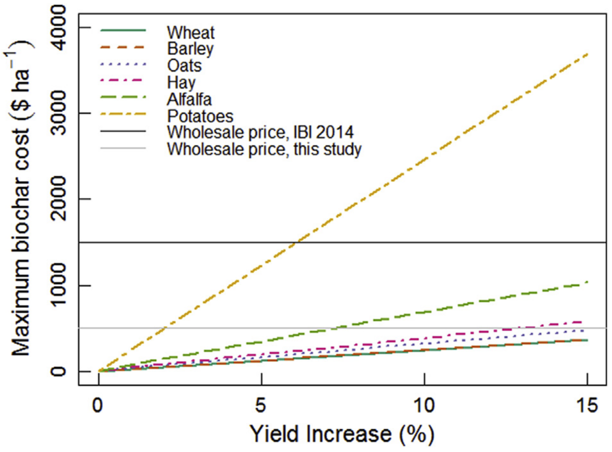

Fig. 6. Maximum cost a farmer could afford to spend on biochar application as a function of yield increase, for major crops of Klamath County (non-organic production). Results assume that yield increases persist for five years and capital costs are 8%.

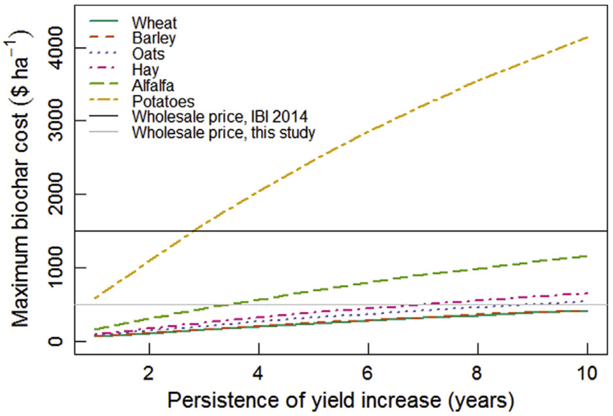

Fig. 7. Maximum costs a farmer could afford to spend on biochar application as a function of the persistence of biochar benefits, for major crops of Klamath County (non-organic). Results assume a 10% increase in yield and capital costs are 8%.

farmers growing a hectare of potatoes and alfalfa could afford to pay substantially higher prices for biochar than farmers growing hay or small grains (Fig. 6.). For example, assuming biochar increases crop yields by 10% per year over 5 years, a farmer growing potatoes could afford to pay up to \$2462 ha^{-1} for biochar, a farmer growing alfalfa could afford up to \$688 ha^{-1}, and farmers growing wheat or barley could only afford biochar at costs of less than \$250 ha^{-1}.

Two estimated costs for biochar provide useful points of comparison to farmers' break-even price (Fig. 6.). The first, from a 2014 survey by the International Biochar Initiative, found the average wholesale price among 28 U.S. producers was \$1500 Mg^{-1} [26]. The second, much lower cost projections from the 45,360 Mg-scale plant developed in this study, suggest biochar costs in the \$500-600 Mg^{-1} range are possible. At the higher cost reported in the 2014 survey, potatoes are the only major crop grown in Klamath County that could support this cost. (Fig. 6.). Potato producers would have to see a crop yield increase of at least 7.5% per year over 5 years to afford a single biochar application of 1 Mg ha^{-1}. However, the lower cost projections developed in this study bring a positive return to alfalfa producers at less than 10% increases in crop yield, with potatoes requiring less than a 3% yield (Fig. 6). Longer persistence levels extend the economic viability of biochar application to other crops, including hay and oats (Fig. 7). Despite this trend (Fig. 7), our current understanding of how long the effects of biochar (or biochar itself) persist is quite limited. Until long-term field studies are conducted across agro-ecosystems, it is unlikely that farmers will assume that cropping systems will continue to reap the benefits of biochar for multiple years. Therefore, our analysis shows that high value crops, like potato and alfalfa, are the primary markets for biochar application.

Possibly the strongest potential market for biochar in the Klamath Basin is organic potato production. Recent prices for organic potatoes were almost three times higher than for conventional potatoes in several U.S. markets [27], and furthermore organic producers are accustomed to higher costs for soil amendments. Therefore, organic growers could afford to pay higher prices for biochar (Fig. 8). However, because the amount of organic acreage in Klamath County is small compared to the amount of conventional acreage, the total biochar market that could be supported by organic growers is small. Although county–level statistics are not available, in 2016, organic potatoes were produced on approximately 1300 ha across the state of Oregon [28]. Even if every organic potato farm amended at an agronomically

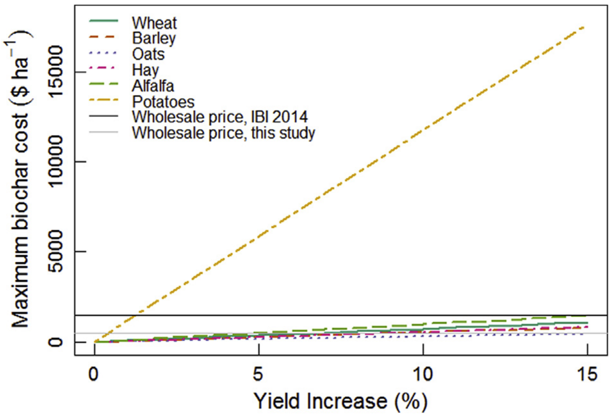

Fig. 8. For organic production, maximum costs a farmer could afford to spend on biochar application as a function of yield increase, assuming that yield increases persist for five years and capital costs are 8%. Crop values are from an Oregon-wide 2016 survey [33].

practical rate of 2.5 Mg ha^{-1}, this would only account for one third of the biochar plant output. Clearly other agricultural markets would need to adopt biochar as well. At biochar prices less than \$500 Mg^{-1} there appears to be a potential economic case. However, currently the biochar demand in Klamath County is small.

Biochar can be applied to the agricultural field along several pathways including spreading and tilling, drilling, or mixing with other field inputs. For organic farmers, nitrogen is added using compost. One pathway would be to mix biochar with compost, preferably during the composting process. Previous studies have shown that biochar is able to absorb ammonium during the composting process, improving air quality and retaining plant available N [29–32]. Blending these processes would add value to both the biochar and the compost, and would harness the existing compost supply chain to deliver biochar. Although the demand for compost in the Klamath Basin is robust (about ~23,000 Mg yr^{-1} (Grant Haigh, Personal communication)), if biochar was added at 5% (vol/vol), the compost market in Klamath Falls would be adequately served by the annual output of biochar from our scenarios.

Although co-composting with biochar has the potential to supply plants with N, the biochar does not have any intrinsic fertilizer value. Therefore, our economic analysis did not consider any cost savings from fertilizer offsets. Likewise, raw biochar may adsorb fertilizer-origin nitrogen from the soil. Our economic analysis also did not consider additional costs that farmers may incur from increased nitrogen inputs. Likewise, our study also did not explore the impact of biochar on other agricultural inputs, including pesticides. Under some circumstances, biochar can act like activated carbon and sorb pesticides used to control weeds, insects, and voles. In these cases, it may be necessary for a farmer to increase the rate or frequency of agrochemical application, which may increase costs. Long-term field studies are needed to better understand the edaphic interactions that may impact farm economics.

In summary, farmers must be able to identify benefits of biochar and to weigh the benefits against the costs. Farmers who lease land for short periods may have less incentive to invest in biochar because the benefits of biochar applications may extend beyond the period of the lease.

4. Conclusions

Biochar production can create an effective link between forest restoration operations and commercial agriculture in landscapes like the Klamath Basin of Oregon. There is ample raw material available in the landscape at low cost to supply a plant designed to consume 43,560 Mg per year of harvest residues [11]. Markets for small-diameter material (10–25 cm) are currently very limited, however, and such material can remain unsold even at pennies on the ton. Despite the lack of market, management plans typically require that it still be cut, forwarded and decked by the road. When unsold, it is later burned *in situ* at additional costs. Material smaller than 10 cm (i.e. tree tops and branches) is used to form a debris layer that protects the soil surface from disturbance during operations; excessive amounts can be piled in openings or at the road. This material can be safely burned onsite during the planned prescribed fire activities after mechanical harvest. Broadcast prescribed fire can be an important element of ecosystem restoration by disposing of fine surface fuels and reducing accumulated fire hazard in these dry forest systems [13]. Widespread forest restoration activities are likely to continue and increase on Forest Service lands in this region to address growing concerns about wildfires [12], making biomass disposal a major regional issue given costs and air quality concerns.

Our marketing discussion assumed that biochar must carry the full cost of its production. Feedstock costs were about one-third of our estimated total biochar production costs. Approximately one-half of the total feedstock cost is related to biomass collection which needed to be done as part of fuel reduction activities. Many of the restoration activities return a surplus from the merchantable material that could be used to offset biomass collection costs under existing federal regulations. Offsetting the collection cost with forest restoration revenues from the merchantable part of the restoration activities could reduce total biochar production costs by 15%, further increasing its marketability.

We have developed a practical design for an industrial-scale biochar production facility to efficiently use this waste material that must be otherwise disposed. The plant, sized to produce about 16,330 Mg of dry biochar per year, will employ approximately 27 people. It will operate year round, but must carry a large product inventory between seasonal deliveries to commercial agricultural customers. The cost of building such a plant on an existing industrial site ranges from \$17 million to \$28 million, depending on its complexity with respect to energy and byproduct recovery. It makes little difference if the site is active or idle, as long as it is in good condition with useable assets, and infrastructure/utility service. Since the biochar production process produces energy-rich gases, it makes practical sense to add the systems necessary to cleanly combust the gases and capture the energy for process use and electric power generation. Whether or not it makes economic sense to do so depends on the cost of purchased electricity and fuels, and the cost of capital.

The “all in” cost of biochar production, including raw material feedstock, direct production, and capital financing costs will range from around \$474 to over \$704 Mg^{-1}. The main drivers influencing biochar production costs are biochar yield, delivered raw material and purchased electricity costs, and the pyrolysis technology selected. Yield, in terms of Mg of biochar per Mg of feedstock, has a very significant influence on all costs. The yield percentages used here were 36% and 37% for thermal and microwave technology respectively and are based on our technology partners' experience and experiments with feedstock supplied from the Klamath Basin.

We have estimated the cost of capital using an 8% interest rate, 20-year productive life, and 20% salvage value for the plant. Under these assumptions, the annual cost of capital increases from a low of \$99 Mg^{-1} of biochar produced under the simple “biochar only” scenario, to \$168 Mg^{-1} in the most complex and expensive plant design scenario, which assumes full energy and liquid byproduct recovery.

This analysis indicates potentially favorable economics for a large-scale biochar plant based on thermal technology constructed at the Worden, OR site. The site is adequately sized and serviced, although the sloped topography is less than ideal. It is in a good location with respect to feedstock supply, utility services, and proximity to agricultural markets. A phased approach might be most practical. The Scenario 2 configuration could be built first to minimize construction cost and operational complexity, with the intention of adding power generation later.

The ability of the commercial agriculture market in the region to absorb the plant's output, at a price that would be attractive to investors, is still under study. The indirect benefits related to linking forest restoration treatments to commercial agriculture have not yet been factored into our economic analysis. If the societal benefits of reducing wildfire extent, frequency and severity; improved health in restored forests; GHG mitigation; and reduced irrigation needs can be monetized and incorporated in the feasibility analysis, we think it likely that an attractive case can be made for supporting development of a biochar industry in the Klamath Basin.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2019.02.015.

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