



## Research paper

## Physical feasibility of biochar production and utilization at a farm-scale: A case-study in non-irrigated seed production



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## ABSTRACT

Despite many demonstrated benefits that biochars can have on agricultural soils, there are few examples of profitable biochar utilization on commercial farms. Barriers to profitability include successfully pairing waste streams, production facilities, and farms where biochar is utilized. However, farm-scale biochar systems, which utilize agricultural wastes as feedstocks and produce energy and biochar for on-farm use, may have efficiency advantages over regional, industrial biochar production. Two critical uncertainties for the feasibility of on-farm production are 1) whether a biochar can be produced from on-farm feedstocks with appropriate qualities for soil amendment, and 2) whether on-farm feedstocks are sufficiently abundant to meet on-farm demand. Here we evaluate these issues for a farm-scale gasification system in NE Washington State that produces biochar from grass seed screenings and straw. Field trials to evaluate the biochar as a liming alternative found it was highly effective when broadcast at a rate of at least 18 Mg ha<sup>-1</sup>. Biochar outperformed hydrated lime in the first year of the study and improved yields by a factor of 2.88 across both years. Biochar produced from on-farm feedstocks were sufficient to amend 6.3–11.8% of the production area annually, translating to a return interval of 9–16 years. Potential co-production of electrical power far exceeded on-farm demand for operating a seed cleaning mill. We conclude that an on-farm biochar production system is physically feasible for meeting demands for both power and liming amendments.

## 1. Introduction

Producing biochar from agricultural residues can create multiple potential benefits for farmers, including energy production, conversion of residues into more persistent carbon forms, and reduced need for off-farm soil amendments [1–3]. Yet there are few examples of profitable biochar use on commercial farms, suggesting that these benefits are difficult to realize simultaneously. Sohi et al. [4] suggested that the major challenge to profitable biochar use is one of optimizing the many discrete components that make up biochar systems. For instance, one challenge is to match biochar properties with soil deficiencies. Some have suggested improving success by creating ‘designer’ or ‘bespoke’ biochars from feedstock combinations and pyrolysis conditions that provide desirable physiochemical properties for specific soils [4,5]. However, decisions about what kind of biochar to produce and use are driven not only by soil needs, but also by availability of feedstocks, by access to gasifier or pyrolysis technology, by whether there is also need

for energy co-production, and by other socioeconomic considerations [4].

When biochar production and utilization is confined to a farm-scale, using only farm-sourced agricultural residues as feedstocks, there are considerably fewer options to consider. There are also many potential benefits to producing and utilizing biochar at a farm-scale in contrast to purchasing it from a regional producer. While a farm-scale system limits the types and quantity of biochar that can be produced, it also allows for a system to be highly customized, to achieve a high level of ‘fit’ between production technology and available feedstocks, and between the biochar properties and soils requiring amendment. Additional efficiency benefits include reduced emissions associated with transportation of feedstocks and finished biochar, and the ability to utilize process heat and couple energy production with on-farm demand. Economically, farm-scale biochar systems may also increase the value of crop residues (because of longer persistence, and higher concentrations of some plant nutrients), and reduce costs for energy and

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conventional soil amendments.

While there are numerous examples of small-scale garden and farm biochar systems using biochar kilns and cook stoves [6–8] and large-scale industrial pyrolysis or gasifier plants that serve regional biochar systems [2,3], there are fewer examples of biochar production on medium- or large-sized farms (i.e. > 200 ha or grossing > \$250,000 USD, [9]). Here, we present a case study of a farm-scale gasification system in NE Washington State, which produces biochar and electricity from Kentucky bluegrass (*Poa pratensis* L.) straw and mill screenings. Of particular interest are two issues that affect the ‘fit’ of the biochar enterprise for the farm. Firstly, are the qualities of biochar co-produced with energy beneficial to the farm's soil and crop production? Secondly, what is the proportion of land that can be amended with biochar relative to the production area providing feedstocks? These two factors—the quality and quantity of biochar that can be produced—are critical to determining the feasibility of a farm-scale system.

The farm has extremely acidic soils (pH 3.9–5), due to historic forest land cover as well as use of ammonium-based fertilizers over many decades [10]. Because very acidic soil and low moisture are primary factors limiting crop production in this region, we anticipated that gasified biochar, which has a high water holding capacity and alkaline pH [11] would be compatible with the cropping system. We further hypothesized that biochar would improve crop yields more than mineral lime for the same nominal increase in soil pH due to additional benefits, which may include the ability to reduce Al phytotoxicity through immobilization of soluble Al [12,13], improved soil moisture and soil permeability, and increased microbial activity. We conducted a field trial in winter wheat (*Triticum aestivum* L. cv. Madsen) over two growing seasons to evaluate the suitability of seed screening biochar as a liming alternative, as well as biochar's influence on soil hydraulic properties, nutrient availability, and microbial communities. Finally, we estimated the potential annual production of biochar from on-farm feedstocks to determine the extent to which on-farm biochar production can meet on-farm demand for liming agents and electricity.

## 2. Materials and methods

### 2.1. Biochar production

Biochar was produced and utilized on a farm in Rockford, Washington, USA. A gasification unit of updraft design was developed for conversion of low-density materials, such as straw and seed screenings, as described by Banowetz et al. [14]. Kentucky bluegrass (KB) seed screenings, obtained from a seed-cleaning mill neighboring the gasifier, were a preferred feedstock due to their compatibility with the gasifier's feed system and their high combustion efficiency [15]. Seed screening biochars utilized in the field study were produced at temperatures ranging from 650 to 750 °C and at a feed rate of 60–82 kg h<sup>−1</sup>. Composition and heating value analyses of both the uncharred seed screening feedstock and the biochars have been reported previously [16].

The gasifier also produces a synthetic gas enriched in CO and CH<sub>4</sub>, which can be combusted by a diesel generator to offset farm electricity requirements, such as operating seed cleaning equipment. Trials that used syngas to replace diesel fuel usage by a generator outputting 100 kW determined an electrical power production of 36 kW continuous output at a feedstock feedrate of 82 kg h<sup>−1</sup>. Furthermore, usable process heat was measured based on the temperature increase of a 114 L water bath circulated through a 14.6 m heat exchanger. The continuous power output as heat was 8.1 kW at the 82 kg h<sup>−1</sup> feed rate.

As reported previously [16], the KB biochar resulting from gasification has a surface area of 26.1 m<sup>2</sup> g<sup>−1</sup>, a bulk density of 0.11 g cm<sup>−3</sup>, a total C content of 35% (SD = 1.5%), a pH of 10.2 (SD = 0.1) and is composed of 16.7% volatile matter, 32.7% fixed carbon, and 50.6% ash by mass of total carbon [11]. Ultimate analyses showed an O/C ratio of 0.019 and an H/C ratio of 0.02, and toxicity analyses found no

detectable PAHs, and very low to non-detectable concentrations of dioxins and furans in extracts [16], making KB biochar a good candidate for use as an agricultural soil amendment.

### 2.2. Field trial

In October 2012 and 2013 test plots were established on a farm in Rockford, WA (47.496°N, 117.111°W, 728 m asl, 450 mm annual precipitation) to determine the suitability of KB seed screening biochar as a liming alternative, impacts on soil and plant nutrients, plant growth and yield, soil moisture and hydraulic properties, and microbial abundance and community composition. KB is the primary crop produced on this diversified farm, with smaller amounts of wheat, canola, and other crops grown for rotation. The test plots were established in a winter wheat crop for broader applicability to this wheat-growing region. Test plots were established in a typical soil for this region (“Freeman” series), which is classified as a fine-silty, mixed, superactive, mesic Aquandic Palexeralf [17]. Four plots each of biochar-amended, lime-amended, and an unamended control were established in a randomized block design with treatments randomized within each block. Because the field was tilled annually, four blocks were established in 2012, and another four in 2013 to compare multiple years. Plot size was 2 × 2 m in 2012, and was enlarged to 4 × 4 m in 2013. Biochar and lime amendment rates were established to increase soil pH by an average of 1 unit from pre-treatment levels of 3.9–5.0, based on rates determined from laboratory mixtures. Biochar (12.1% CaCO<sub>3</sub> equivalence) was applied at a rate of 18 Mg ha<sup>−1</sup> (equivalent to 1.2% by mass in the top 10 cm, or 6% by volume). Hydrated lime (Ca(OH)<sub>2</sub>, 136% CaCO<sub>3</sub> equivalence) was applied at a rate of 0.02 Mg ha<sup>−1</sup>. Both amendments were incorporated with a rototiller to 10 cm. Following soil application, the field was sown to winter wheat in rows with 18 cm spacing.

Test plots were harvested and soil samples collected 10 months after the amendment in the first week of August of each year. Soil cores 2.5 cm in diameter were removed from 0–10 cm and 10–20 cm depth intervals at 5 unique locations per plot and aggregated. Total above-ground biomass was harvested from the undisturbed 1 × 1 m center of each plot, and seeds were separated using seed cleaning instrumentation at the National Forage Seed Production Research Center in Corvallis, OR. Soil water infiltration rates and hydraulic conductivity were measured in the undisturbed plot centers, using a single ring infiltrometer (30.5 cm dia. × 20.3 cm height, inserted 7.6 cm) with falling head, by timing the infiltration of repeated 2 L water additions. Soil compaction was measured using a soil penetrometer (DICKEY-john Corporation, Illinois, USA) at five random locations between the crop row at depth intervals of 0–2.5, 2.5–5, 5–7.5, and 7.5–10 cm. Soil and plant analysis methods were reported previously by Trippe et al. [18,19] and are also described in the supplemental material. Climatic conditions during each year were evaluated from a NOAA weather station located at Spokane Felts Field [20], which is 25 km away but provides a close approximation for conditions at the farm.

We also examined soil amendment impacts on soil microbial abundance and community composition from soil samples collected in April and June 2014 from the second year plots only. Extended methods are provided in the supplementary material. Briefly, fungal and bacterial abundance were inferred from quantitative PCR (qPCR), which measures the copy number of either the 16S bacterial rDNA or the internal transcribed spacer (ITS) region of the fungal rDNA per ng of soil DNA. The structure of the microbial community was examined by measuring the variation in ribosomal DNA with terminal restriction length polymorphism (T-RFLP) analyses as described in Reardon and Wuest [21].

### 2.3. Data analysis

Treatment differences in plant biomass and plant and soil chemistry were analyzed with a linear mixed-effects model, with blocks

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