Agriculture **2013**, *3*, 715-725; doi:10.3390/agriculture3040715

OPEN ACCESS

agriculture

ISSN 2077-0472

www.mdpi.com/journal/agriculture

Article

Practicality of Biochar Additions to Enhance Soil and Crop Productivity

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Received: 25 August 2013; in revised form: 12 September 2013 / Accepted: 25 September 2013 / Published: 17 October 2013

Abstract: The benefits of biochar to soils for agricultural purposes are numerous. Biochar may be added to soils with the intention to improve the soil, displace an amount of conventional fossil fuel based fertilizers, and sequester carbon. However, the variable application rates, uncertain feedstock effects, and initial soil state provide a wide range of cost for marginally improved yield from biochar additions, which is often economically impracticable. The need for further clarity on optimizing biochar application to various crop yields is necessary if it is to gain widespread acceptance as a soil amendment.

Keywords: biochar; carbon sequestration; economic analysis; soil amendment

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1. Introduction

Soil health is the foundation of a vigorous and sustainable food system [1]. Plants obtain their nutrition from organic matter and minerals found in soils. As the land is farmed, the agricultural process disturbs the natural soil systems including nutrient cycling and the release and uptake of nutrients [2]. Modern agriculture is apt to mine the soil for nutrients and to reduce soil organic matter levels through repetitive harvesting of crops. This decline of the soil continues until management practices are improved, additional nutrients are applied, rotation with nitrogen-fixing crops is practiced, or until a fallow period occurs allowing a gradual recovery of the soil through natural

ecological development. As the natural stores of the most important nutrients for plant growth decline in the soil, growth rates of crops are inhibited. The most widespread solution to this depletion is the application of soil amendments in the form of fertilizers containing the three major nutrients: nitrogen, phosphorus, and potassium. Among these nutrients, nitrogen is considered the most limiting for plant growth. Nitrogen builds protein structures, develops hormones, chlorophyll, vitamins, and enzymes, and promotes stem and leaf growth.

Inorganic or commercial fertilizers have been the primary soil amendment since the dawn of the industrial age. Nitrogen fertilizers are often made using the Haber-Bosch process utilizing natural gas (CH_4) for the hydrogen and nitrogen gas (N_2) from the air to form ammonia (NH_3) as the end product. This ammonia is used as a feedstock for nitrogen fertilizers, such as anhydrous ammonium nitrate (NH_4NO_3) and urea ($CO(NH_2)_2$) [3].

However, the use of fossil fuel based fertilizers contributes to greenhouse gas emissions while similarly encouraging the depletion of the natural nutrient and minerals in healthy soils. Biochar, the solid material obtained from the carbonisation of biomass though pyrolysis, is a potential soil amendment and carbon sequestration medium [4]. Pyrolysis is a thermochemical process where biomass is heated in the absence of oxygen, whereby the resulting char is primarily stabilized carbon [5]. The net effect of biomass pyrolysis to biochar is to remove carbon dioxide, storing it in stable soil carbon "sinks". Pyrolysis can be optimized to produce a number of primary and secondary products such as synthesis gas with differing energy values (syngas), liquid and char [6]. When char is intentionally produced for agricultural or environmental use it is called biochar [4]. When used as a soil amendment, biochar applied to the soil has been reported to boost soil fertility and improve soil quality resulting in increased crop yields. Soil benefits include raising soil pH, increasing moisture holding capacity, attracting more beneficial fungi and microbes, improving cation exchange capacity (CEC), and retaining nutrients [7,8]. These benefits have been shown to increase yield in biomass and crops under variable conditions [9–13].

The term "biochar" is relatively new, yet biochars in one form or another have been used throughout history, mainly for soil improvement. One of the first historical mentions of biochar use for soil improvement dates back at least 2000 years [14]. In the Amazon Basin, there exists evidence of extensive use of biochar in the fertile soils known as Terra Preta (black soil) and Terra Mulata (mulatto earth), which were created by ancient, indigenous cultures of the time most likely to enhance localized soil productivity [14]. To this day, the terra preta soils in the region remain highly fertile compared with other soils of the region (e.g., Oxisols and Ultisols), often containing as much as 4 times more organic matter in the top 30 cm of the soil [15].

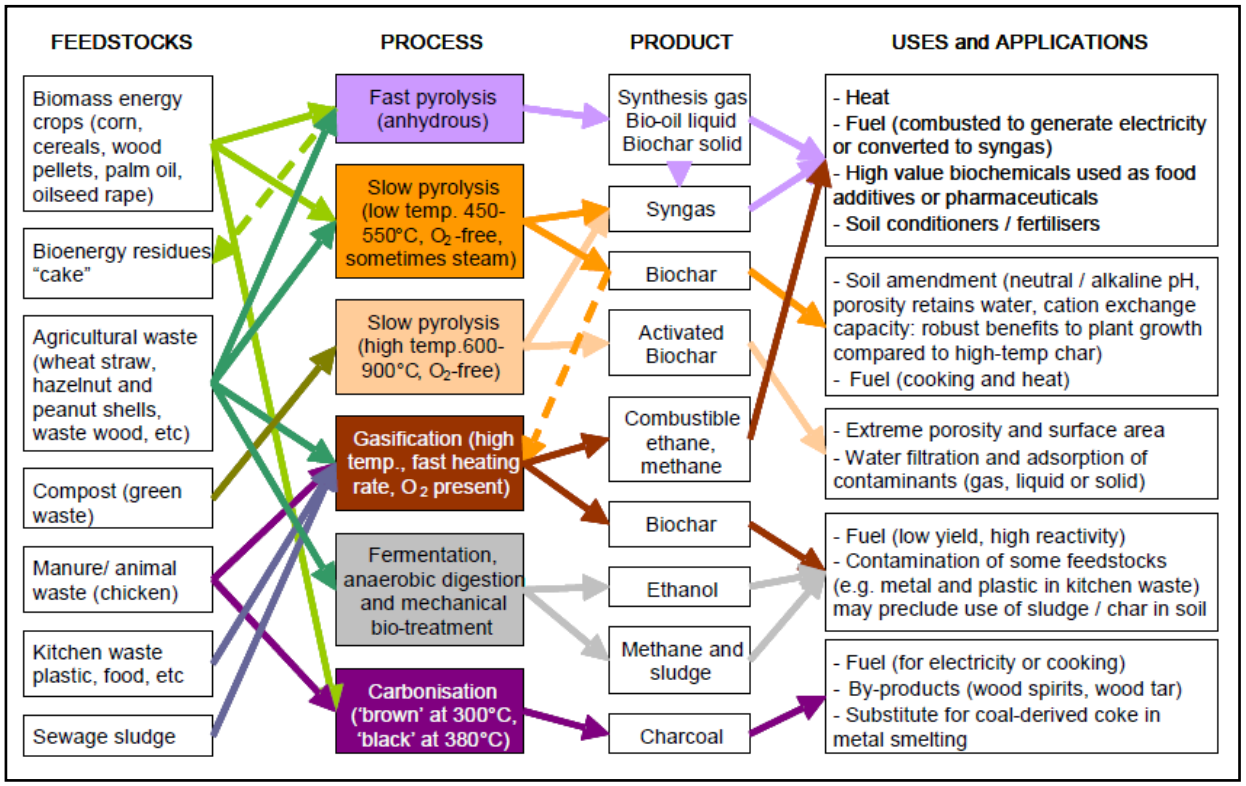
2. Biochar Feedstocks and Pyrolysis

A number of reviews and studies have focused on the potential benefits of using biochar as a soil amendment [16–19]. Biomass pyrolysis and gasification are well established technologies for the production of biofuels and syngas. However, commercial employment of biochar as a soil amendment is still in its infancy. The effect of biochar as a soil amendment on crop productivity is variable due primarily to interactions and processes that occur when biochar is applied to soil, which are not yet fully understood [20]. Currently, Japan has the largest market for biochar products; approximately

15,000 tons/year is traded annually for soil use [21]. The pyrolysis process affects the qualities of the biochar produced and its potential value to agriculture in terms of soil performance or in carbon sequestration. The temperature and time the biomass is in the pyrolysis kiln, along with various feedstock types determines the nature of the product.

Feedstock and process condition affect the characteristics of the biochar produced. The thermal profile and feed choice in addition to the geographic variations in soil type and climate are some of the chief sources of variability when looking to benefits of biochar as a soil amendment. Feedstocks currently used at a commercial scale or in research facilities include wood waste, crop residues (including straw, nut shells, and rice hulls), switch grass, bagasse from the sugarcane industry, chicken litter [22], dairy manure, sewage sludge [23] and paper sludge. Biomass energy crops processed by slow pyrolysis such as cereals and wood along with agricultural wastes including wheat straw and peanut shells result in a char suitable for soil amendment (Figure 1). Green waste as plant prunings and grass clippings [11] and wastewater sludge [24] have also been employed as soil amendments.

Figure 1. Summary of common biochar feedstocks, typical products, applications and uses of these products. Note: this figure is reproduced with permission from [25]. Copyright Elsevier, 2009.



A key differentiation between biochar feedstocks can be made between biochars made from nutrient rich feedstocks such as animal manures or sewage sludge, and biochars produced from lignin rich plant biomass feedstocks. Typically, biochars produced from nutrient rich manures will have a high nutrient content and supply potential. Livestock biochars are chemically distinct from other biochars (e.g., those made from wood or crop residues) because of their higher content of nitrogen, phosphorus,

potassium, and other nutrients similar to the qualities of conventional commercial fertilizer [26]. However, some of the nutrients contained in the biochar are not available to plants.

2.1. Biochar Cost Estimates

The cost of biochar is directly related to the cost of the feedstock, collection and transportation cost, the processing method of the feedstock in use and the value of any co-products. Biochars created from agricultural and green waste, poultry litter and wastewater sewage differs in cost to produce. Green waste and waste wood biochars were found to cost between $150 to $260/ton [27]. Van Zwieten [28] gives an estimate of biochar produced from bagasse at $50 to $200/ton. The US Biochar Initiative [29] reports the broad cost of biochar as $500/ton. The cost of chars from poultry litters and wastewater sludge are much lower or even negligible, as currently these wastes typically have a cost associated with their disposal. Our unpublished data suggest costs of production may be as low as $50/ton.

The cost to commercially apply biochar to the field is not yet well established. Williams and Arnot [30] examined the costs associated with two common methods of biochar application, the broadcast and disk and the trench and fill. They found that to apply 25 tons/ha by the broadcast and disk method was approximately $63/ha and $70/ha using the trench and fill method.

2.2. Crop Productivity and Biochar Application Rates

Along with improved soil health, increased crop yield is generally reported with application of biochar to soils. However, many of the published experiments are highly variable and dependent on many factors, mainly the initial soil properties and conditions and biochar characteristics. Positive crop and biomass yield was found for biochar produced from wood, paper pulp, wood chips and poultry litter [31]. In some studies corn yield was improved 140% [32], cowpea by 100% [33], while radishes grown with poultry litter biochar yielded a 96% increase [34].

A meta-analysis of the available literature performed by Jeffery *et al.* [31] found a 10% mean yield increase in crop productivity as a percentage of the control at application rates of 10, 25, 50 and 100 tons/ha. These findings were confirmed by more recent reviews by Liu *et al.* [35] and Biederman and Harpole [36]. Liu *et al.* [35] reviewed published data from 59 pot experiments and 57 field experiments from 21 countries and found crop productivity was increased by 11% on average. Liu found benefits at field application rates typically below 30 tons/ha field application and reported that increases in crop productivity varied with crop type with greater increases for legume crops (30%), vegetables (29%), and grasses (14%) compared to cereal crops corn (8%), wheat (11%), and rice (7%).

Biederman and Harpole [36] analyzed the results of 371 independent studies. This meta-analysis showed that the addition of biochar to soils resulted in increased aboveground productivity, crop yield, soil microbial biomass, rhizobia nodulation, plant K tissue concentration, soil phosphorus (P), soil potassium (K), total soil nitrogen (N), and total soil carbon (C) compared with control conditions. However, they found no obvious trend in production with reported biochar application rates. They found that variability in crop production increased with application rates.

Biochars produced from biosolids or sewage might also increase yields. Hossain *et al.* [24] applied wastewater sludge biochar at 10 tons/ha to cherry tomatoes resulting in increased production by 64%

above the control soil conditions. The yield gains were attributed to the combined effect of increased nutrient availability (P and N) and improved soil chemical conditions resulting from the biosolid based amendment. However, there exists the concern of heavy metal contamination from biochars produced from sewage sludge. The inconsistency of sewage sludge might contain differing amounts of toxic metals [37] which limit the land application due to food chain contamination.

However, there appears to be an upper limit on the application of biochar additions and crop productivity. Lehmann *et al.* [7] notes that crops respond positively to biochar additions up to 55 tons/ha, showing growth reductions only at very high applications. The findings of Biederman and Harpole [36] also confirm instances of decreasing yield due to a high biochar application rate. When the equivalent of 165 tons/ha of biochar was added to a poor soil in a pot experiment [10], yields decreased to the level of the unamended control. Kammann *et al.* [38] also found that quinoa growth was retarded at 100–200 tons/ha. Others have reported thresholds at much lower levels. Asai *et al.* [39] reported greater rice yields with 4 tons/ha of biochar compared with 8 or 16 tons/ha applied, with the higher application rates providing yields not different from the unamended control. The reasons for these decreases are not known; further study is necessary to determine which biochar materials are best suited for application and at which rates to specific soils.

The recommended application rates of biochar as a soil amendment are quite variable given the insufficient field data available to make general recommendations on biochar application rates according to soil types and crops. Additionally, biochar feedstock materials vary widely in their characteristics (e.g., pH, nutrient levels, ash content) which would also influence application rate. Since biochar does not appreciably decompose in soil, a single application can provide positive effects over several growing seasons in the field [9,32] as is not usually the case for manures, compost, and conventional fertilizers. Whilst much remains to be established, a onetime application of 25 tons/ha to a typical field crop seems reasonable to achieve the marginal benefits reported above. However, most biochar materials, unless derived from manure or blended with nutrient rich materials, do not substitute for conventional fertilizer, so adding biochar without necessary amounts of nitrogen (N), phosphorus (P) and potassium (K) should not be expected to provide improvements to crop yield.

2.3. Displacement of Conventional (Fossil Fuel Based) Fertilizer

One of the reasons for the observed increase in crop yield with biochar application is the increase of nitrogen utilization from the applied fertilizer [9,40]. This is the result from the decrease of nitrogen lost due the increase of soil CEC with biochar application [34,41] or because of the ability of biochar to inhibit nitrate transformation by fertilizer [40].

As biochar applications provide greater nutrient retention, this implies that less conventional fertilizers need to be applied to achieve a given crop yield. Because the vast majority of nitrogen fertilizer is derived from natural gas (CH_4) via the Haber-Bosch process, Gaunt and Cowie [42] in an assessment of biochar's ability to reduce greenhouse gases, have estimated a 10%–30% reduction of nitrogen fertilizer use. Zhang *et al.* [43] estimate that for approximately every ton of N fertilizer manufactured and utilized, 13.5 tons CO_{2e} is emitted.

Additionally, Sohi *et al.* [25] have suggested the concept of using syngas from the pyrolysis process to replace the natural gas to produce nitrogen. Combining the biochar and nitrogen that is produced in

the same process can create a powerful carbon and nitrogen rich fertilizer based on the research done by Day *et al.* [44].

2.4. Carbon Markets

The potential to sequester carbon in biochar is an additional benefit to soil application. Once biomass is pyrolyzed, the sequestered carbon is long lasting. Kuzyakov *et al.* [45] assessed a half-life of 1400 years for the carbonized materials in biochar. Avoided emissions from biochar conversion of green waste (using slow pyrolysis) may be as high as 3.8 tons/CO_{2e} ton dry feedstock [42]. This value assumes benefits from avoided emissions at landfill, fossil fuel substitution and other greenhouse gas benefits.

Gaunt and Cowie [42] discuss that avoided emissions associated with biochar production and use are generated via a number of pathways. Diversion of feedstock for biochar production provides a situation which may lead to avoided emissions of methane (CH_4) and nitrous oxide (N_2O), where the energy produced during pyrolysis displaces fossil fuels may also represent and avoided emission. Reduction in nitrogen fertilizer inputs results in avoided emissions by less use of fossil fuel during manufacture and reduced losses from soil as N_2O. Additionally, savings in irrigation and reduced energy use in cultivation may lead to further avoided emissions while increased yields can result in C sequestration.

A "carbon offset" is the term used to describe a verified and certified emission reduction or sequestration of one ton of CO_{2e}. Carbon markets allow polluters who can reduce their emissions, or those who can create a C offset, to trade their extra emission credits with others who can only do so at a higher cost, thus achieving an emissions target in a cost effective way. Carbon markets are currently in an early stage of development. Recent market prices in the European trading system have ranged between \$5–30 per ton CO_{2e} during 2008–2013. However, Stern [46] assessed the long term projections suggest a value of \$100/ton CO_{2e}.

For this paper we assume that the C stabilized in biochar represents approximately 75% of C in the feedstock, stable over 100 years. Since then biochar contains 75% C, the CO_{2e} sequestered for one ton of biochar is 2.06 tons CO_{2e}.

3. The Case for Biochar Applications to Soil

As biochar is expected to have enduring soil benefits, whereby it does not need to be added to soil each year as is the case with many agricultural fertilizers, the potential exists where it may improve otherwise unproductive soils into the future. Biochar from woody materials is typically a soil enhancer, enhancing the pH, soil water relations and CEC, resulting in improved crop yields [47].

Additionally, biochar from agricultural livestock waste such as cow manure and poultry litter has the added benefit of providing higher levels of essential nutrients (N, P, and K) [26]. However, not all of the nutrients contained in the biochar are available to plants as additional research is necessary to understand how manure biochars interacts with specific crops and soils to reduce nutrient leaching and increase nutrient uptake in crops [48].

3.1. Economical Use of Biochar Derived from Lignin Rich Feedstocks

As evidenced from the previous discussion, there is a growing body of literature and enthusiasm for the use of biochar in agriculture. However, what seems to be lacking in the literature is a critical assessment of the economic viability of biochar use. The following analysis is intentionally superficial as there exists a high degree of uncertainty that surrounds the indirect impacts of biochar application to soils (effects on productivity, soil benefits, conventional fertilizer reduction, *etc.*), in addition to the unsettled value of carbon sequestration, precludes a precise valuation of the costs and benefits.

The majority of published biochar research to date using lignin rich feedstocks can be interpreted and is relevant to the use of biochar as a soil amendment and conditioner. Further the majority of this research has been undertaken in row crop agriculture with crops such as corn and wheat. Taking corn cropping as an illustrative example of the feasibility of biochar soil additions reveals less than ideal economy.

Using USDA statistics, the average gross value of corn production for corn grain and silage was on average $2,024/ha for 2011 and 2012 [49]. The cost of fertilizer inputs was $377/ha and the total cost of production was $1,545/ha [49] giving a net profit of $479/ha. This provides an important context for the economic feasibility of biochar applications. A US farmer makes less than $500/ha from growing corn, so any change in growing practice will need to be justified in the context of this financial return.

Based on literature reviewed above, an increase in production of around 10% may be expected which would increase the gross value by $203 and we assume 25% savings in input costs ($94), giving a total potential increase in net profit $297/ha.

Considering the input and application costs coupled with application rates of biochar soil additions, an approximate cost for biochar amendment is $6,317/ha (Table 1).

Table 1. Range and practical estimate of the total cost/ha of biochar soil application benefits.

Variable	Range of Reported Ralues	Estimate	Rate	Total
Biochar cost/ton	$0 to $500	$250	25	$6,250
Application cost 25 tons/ha	$63 to $70	$67	1	$67
Total cost/ha				$6,317

We use a net present value analysis (NPV) to assess whether this investment is economically viable. A NPV of $0 suggests that an investment would neither gain nor lose value. Assuming a discount rate of 10% (the rate of return that could be earned on an investment in the financial markets with similar risk) and a 10 year return, the NPV is −$4,494 (Table 2). This reveals that investing $6,317 in a biochar soil amendment is not economically viable. Further analysis shows that a breakeven cost for biochar of $70.23/ton or less would be justified to achieve the 10% increase in yield coupled with a 25% fertilizer savings (Table 2).

To assess the potential impact of C offset revenues on the economics of biochar application we assume that the carbon offset revenue can be used to reduce the cost of biochar to a farmer. We first assess the impact of a value of $10/ton CO_{2e} for the biochar C offset. At $10/ton CO_{2e} the price that can be paid for biochar can be increased from $70 to $91/ton biochar, still well below current market prices for biochar. A C offset value of $87.5/ton CO_{2e} is required to bring the effective value of biochar

to \$250/ton whilst maintaining a NPV of zero. A value of \$87/ton CO_{2e} is considerably above current market prices, but below the value anticipated by Stern [46].

Table 2. Breakeven analysis of biochar soil application.

Variable	Value	Break Even	Break Even Carbon Price Support	
Gross value of production (\$/ha)	\$2,024	\$2,024	\$2,024	\$2,024
Cost of fertilizer input (\$/ha)	\$377	\$377	\$377	\$377
Rate of biochar applied (ton/ha)	25	25	25	25
Avoided emissions (ton CO_{2e}/ton biochar)	2.06	2.06	2.06	2.06
Cost of biochar (\$/ton biochar)	\$250	\$70	\$91	\$250
Cost of application (\$/ha)	\$67	\$67	\$67	\$67
Yield Increase (%)	10%	10%	10%	10%
Fertilizer savings (%)	25%	25%	25%	25%
Fixed cost (\$/ha)	\$1,545	\$1,545	\$1,545	\$1,545
Market price for carbon (\$/ton CO_{2e})	\$0	\$0	\$10	\$87.5
Net profit (\$)	\$479	\$479	\$479	\$479
Annual discount rate (%)	10%	10%	10%	10%
Investment in biochar application after C revenues (\$/ha)	\$6,317	\$1,823	\$1,241	\$211
NPV (10 year)	\$4,494	\$0	\$0	\$0

4. Conclusion

From this cursory analysis it can be seen that the economics of biochar use as a soil conditioning amendment are challenging. The 10 year breakeven cost of \$1,823/ha contrasts with estimates from the literature that biochar soil application would cost ~\$6,000/ha (Table 1). A C market value of \$87.5/ton CO_{2e} would be necessary to subsidize the current cost estimate of biochar. This analysis signals the challenges that face biochar research. In many situations the costs and risks associated with trying to achieve the yield gains and fertilizer savings reported will mean that the reported application rates of biochar may not be economically beneficial.

It is clear that biochar has the potential to be sold as a direct substitute for fertilizer and soil amendment. When sold as a substitute for fertilizer the costs need to be bounded by the annual fertilizer costs. Further research to determine the optimal biochar application with a focus on strategies to reduce the quantities of biochar required to deliver desired benefits may drive down the ultimate cost of the application. Further, if the goal is to deliver economically viable biochar, use strategies focused on high value crops that require high levels of fertilizer application may prove more fruitful.

Long-term field research focusing on an optimal combination of nutrient use, water use, carbon sequestration, avoided greenhouse gas emissions, and changes in soil quality and crop productivity is needed before large-scale biochar application to soils are to become practical.

Conflicts of Interest

The authors declare no conflict of interest.

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