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The economic value of biochar in crop production and carbon sequestration

Suzette P. Galinato [a,*], Jonathan K. Yoder [b], David Granatstein [c]

[a] IMPACT Center, School of Economic Sciences, Washington State University, Pullman, WA 99164, USA
[b] School of Economic Sciences, Washington State University, Pullman, WA 99164, USA
[c] Center for Sustaining Agriculture and Natural Resources, Washington State University, 1100N. Western Ave., Wenatchee, WA 98801, USA

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ABSTRACT

This paper estimates the economic value of biochar application on agricultural cropland for carbon sequestration and its soil amendment properties. In particular, we consider the carbon emissions avoided when biochar is applied to agricultural soil, instead of agricultural lime, the amount of carbon sequestered, and the value of carbon offsets, assuming there is an established carbon trading mechanism for biochar soil application. We use winter wheat production in Eastern Whitman County, Washington as a case study, and consider different carbon offset price scenarios and different prices of biochar to estimate a farm profit. Our findings suggest that it may be profitable to apply biochar as a soil amendment under some conditions if the biochar market price is low enough and/or a carbon offset market exists.

1. Introduction

Biochar is a charcoal-like material produced by the thermochemical pyrolysis of biomass materials. It is being considered as a potentially significant means of storing carbon for long periods to mitigate greenhouse gases (Laird, 2008). Much of the interest in biochar comes from studies of Amazonian soils that appear to have been amended with biochar, with significant improvements in soil quality and positive effects on crop yields (Lehmann et al., 2004). These changes have persisted for hundreds, if not thousands, of years. It is not yet known how long it takes for biochar to integrate with the soil and express its benefits. However, biochar represents a stable form of carbon and thus provides an intriguing potential carbon storage strategy as a soil amendment (Mathews, 2008).

This study assesses the potential value of the use of biochar as a soil amendment from potential dual benefits of increased crop yields and returns from carbon sequestration, under a set of assumed conditions. We consider the effect of biochar in improving crop productivity by ameliorating the soil acidity. Next, we evaluate and aggregate emissions avoided and carbon sequestered when biochar replaces lime usage in the field. We then calculate the value of carbon offsets using a low and high price range of \$1 and \$31/MT CO_2, assuming a carbon trading mechanism exists for biochar soil application. As a case study, we focus on wheat production in Washington State and examine farm profitability with and without the application of biochar. Our findings suggest that it may be profitable to apply biochar as a soil amendment under some conditions if the biochar market price is low enough and/or a carbon offset market exists.

The existing literature will be reviewed in detail below. As will be discussed, some of these studies focus on the properties and application rates of biochar and their impacts on agricultural productivity, and some examine biochar's potential in sequestering carbon. However, this is the first study to our knowledge that links farm profitability with the economic value of biochar as a soil additive and as a source of carbon offset credits.

The following two sections provide a review of existing studies of the impacts of biochar soil application to crop productivity and to carbon (C) sequestration. We rely on the results of these studies in our analysis of the economic value of biochar as a soil amendment. Section 4 describes our methodology, and Section 5 presents estimated costs and returns in crop production for the case of wheat, with and without the application of biochar. Section 6 concludes.

2. Impacts of biochar on crop productivity—related studies

A number of studies have investigated the response of crops to biochar application. Table 1 presents summaries of a limited sample of these studies showing the impacts of biochar on crop response in terms of yield or plant biomass. Observed impacts vary depending on interactions between the types of biochar used, crop studied, soil type, local conditions, among others. Some studies have observed increased crop productivity from using biochar alone (Baum and Weitner, 2006; Chan et al., 2008). Other studies found a more positive crop response when biochar is

* Corresponding author. Tel.: +1509 335 1408; fax: +1509 335 3958.
E-mail address: sgalinato@wsu.edu (S.P. Galinato).

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Table 1
Summary of studies on biochar used as a soil amendment.

Author(s)	Location	Soil type	Type of biochar	Biochar application rate	Crop
Kishimoto and Sugiura (1985)[a,b]	Japan	Volcanic ash soil, loam	Unknown wood	0, 0.5, 5.0, and 15.25 t/ha	Soybean
Crop response: at 0.5 t/ha, increased yield by 51%. At 5 t/ha and 15.25/ha, reduced yield by 37% and 71%, respectively. Reductions were attributed to micronutrient deficiency induced by an increase in pH.					
Mikan and Abrams (1995)[b]	United States (Pennsylvania)	Forest area on relic charcoal hearths	Wood for charcoal production	Unknown	Vegetation in hearth and non-hearth areas compared after 110 years
Crop response: tree density and basal area were reduced by 40%.					
Young et al. (1996)	United States (Appalachian mountains)	Forest area on relic charcoal hearths	Wood for charcoal production	Unknown	Trees
Crop response: lower overstory tree cover and density on relic charcoal hearths than on adjacent, non-hearth areas. The richness and diversity of overstory and understory tree cover as well as ground vegetation were consistently lower on hearths.					
Glaser et al. (2002)	Brazil	Xanthic ferralsol	Secondary forest wood	0, 68, and 136.75 t/ha	Rice, cowpea
Crop response: at application rate of 68 t/ha, biomass increased by: 20%, rice; 50%, cowpea compared to control treatment where no biochar was applied. At application rate of 136.75 t/ha, biomass of cowpea increased by 100%.					
Steiner (2006)[c]	Brazil	Xanthic ferralsol	Wood	11.25 t/ha	Banana
Crop response: reduced soil acidity and increased *K* uptake					
Yamamoto et al. (2006)[c]	Indonesia	Acid soil	Bark	15.25 t/ha	Maize
Crop response: higher yields with biochar and fertilizer, than fertilizer alone					
Steiner et al. (2007)	Brazil	Xanthic ferralsol	Secondary forest wood	11.25 t/ha	Rice, sorghum
Crop response: charcoal plus mineral fertilizer improved yield by a factor of 1.5–2 and improved stover by a factor of 1.3–1.4. Using charcoal plus compost and/or fertilizer, yields are consistently greater (i.e., 4–12 times greater) compared to using fertilizer alone.					
Van Zwieten (2007)	Australia	Semi-tropical soil		10 t/ha	Wheat, soybeans
Crop response: wheat: biomass tripled. Soybeans: biomass more than doubled. Percentage increase in biomass is the same when nitrogen fertilizer is applied together with biochar. Biochar raised soil pH at about 1/3 the rate of lime.					
Van Zwieten et al. (2007)[b]	Australia	Ferrosol	Paper mill sludge	10 t/ha	Wheat
Crop response: 30–40% increase in wheat height in acidic soil but not in alkaline soil. Response was attributed mainly to the liming value of biochar.					
Collins (2008)	Washington	Quincy sand, hale silt loam	Peanut hull (PH), fir bark (SB)	0, 12.5, 25, and 50 t/ha	Wheat
Crop response: Quincy: root–shoot ratio of wheat decreased in all application rates of biochar. Hale: using PH, decline in root–shoot ratio of wheat at 25 t/ha of biochar compared to nil; no change at 12.5 and 50 t/ha. Hale: using SB, root–shoot ratio of wheat increased in all treatments. 0.5–1 unit increase in soil pH due to biochar addition.					
Chan et al. (2008)	Australia	Alfisol	Poultry litter	0, 10, 25.25, and 50.5 t/ha	Radish
Crop response: With biochar, without N fertilizer: yield increased from 42% at 10 t/ha of biochar to 96% at 50.5 t/ha of biochar, relative to the yield from unamended control.					
Van Zwieten et al. (2008)[c]	Australia	Ferrosol	Poultry litter (PL), paper mill waste (PM)	Maize: 0.5–50.5 t/ha PL. Beans: 10 t/ha PL and PM versus 3 t/ha lime	Maize, faba beans
Crop response: maize: 51% yield increase at 10 t/ha; and 109% yield increase at 50.5 t/ha compared to nil. Beans: yields are the highest with biochar plus fertilizer, compared to biochar alone. PL biochar outperformed lime amendment.					

Sources:

[a] Adopted from Glaser et al. (2002).
[b] Adopted from Chan and Xu (2009).
[c] Adopted from Blackwell et al. (2009).

applied together with fertilizers (Steiner et al., 2007). However, some studies have found negative crop response to biochar soil amendments. For example, Kishimoto and Sugiura (as cited in Chan and Xu, 2009) reported reductions in soybean yields with higher application rates of biochar. Collins (2008) found a decline in the root–shoot ratio of wheat in Quincy sand soil amended with peanut hull biochar and softwood bark biochar compared to unamended soil.[1] An increase in the root–shoot ratio of wheat, however, was found in Hale silt loam soil amended with softwood bark biochar. Collins (unpublished data) also found a significant increase in soil water holding capacity on silt loam soils but not on sandy soil. This could potentially increase crop yields in a dryland production region that is often water-limited for yield. Lehmann et al. (2006) discussed a greenhouse study in Columbia where biochar application led to low N availability to crops. Leguminous crops were found to compensate for this due to biological N_2 fixation induced by biochar application. On the other hand, non-legume crops were found to require additional N fertilizers due to low N availability. The above studies are controlled, small-scale experiments. At this point, it is not possible to draw conclusions on the effect of biochar that can be broadly applied, especially in temperate regions with younger

[1] The root/shoot ratio is the ratio of below-ground level biomass and above-ground level biomass.

Table 2
Selected characteristics of six biochars (slow pyrolysis at 500 °C) used in the laboratory analyses.
Source: Collins (2008).

Source of biochar	Biochar characteristics					
	C (%)	N (%)	S	C:N	C:S	pH
Switchgrass	60.5	2.06	0.20	30	350	9.4
Digested fiber	66.7	2.23	0.30	30	228	9.3
Peanut hull	70.6	1.74	0.04	41	1203	9.6
Bark (UGA)	74.5	0.34	0.03	220	2833	7.6
Softwood bark	77.8	0.44	0.06	176	1482	8.4
Wood pellets	80.0	0.14	0.04	588	1855	7.4
Activated charcoal	87.3	0.47	0.80	186	114	9.1

Note: activated charcoal is included as a standard analysis and comparison to biochar.

soils (compared to highly weathered soils in more tropical environments). Furthermore, biochar itself will not contribute meaningful amounts of nutrients given its high stability. For example, Granatstein et al. (2009) found that biochar did not significantly increase the cation exchange capacity on the Quincy sand in their study, the one soil where an increase would be most likely seen; but biochar did increase soil C. In Collins (2008), total nitrogen in the soil increased (although at small amounts) after addition of biochar. This does not, however, imply that a lesser amount of N fertilizer may be needed when biochar is added to the soil. The study found that N in biochar is not available to plants; rather, it is fused in the C matrix. Therefore, the potential for biochar to reduce chemical fertilizer requirements remains unclear. Nonetheless, the evidence from available studies does show that soil application of biochar often affects crop productivity and can be beneficial in some situations. Highly weathered soils, such as those found in humid tropics and the southeastern US, may experience more soil chemical and biological benefits from biochar additions (e.g., improved pH, cation exchange capacity, and overall nutrient status) than the young soils typical of Washington State, the source of the soils for the study reported here.

One consistent effect of biochar amendment has been change in soil pH (most frequently raising it), which implies a liming value of biochar. Collins (2008) found nearly a unit increase in soil pH with biochar derived from herbaceous feedstocks (switchgrass, digested fiber) and 0.5–1 unit increase in the soil pH with biochar derived from woody sources (softwood bark, wood pellets) (Table 2). Van Zwieten et al. (2007) also reported an increase in the soil pH and 30–40% increase in the height of wheat when biochar was applied to an acidic soil. Rondon et al. (2007) credited the improvement of bean productivity due to the elevation of soil pH and other soil nutrients as a consequence of biochar use. Biochar may be considered a potential substitute for agricultural lime, especially in agricultural regions that have acidic soils. However, a unit change in the soil pH would require 1.35 metric ton (MT) to 9.78 metric tons per hectare (ha) of agricultural lime, depending on the soil type (CPHA, 2002). For example, a sand soil type requires 1.35 MT/ha of lime to increase the soil pH by a unit as compared to about 42.5 MT/ha biochar[2] needed to achieve the same desired change in soil pH (Collins, 2008). Thus, it may not be economically feasible for farmers to use biochar in crop production solely for pH adjustment since it would entail a relatively higher cost compared to agricultural lime. On the other hand, other potential benefits from adding biochar to the soil such as avoided emissions of lime and the capacity of biochar to sequester carbon (to be discussed in the next section) should be considered. It is possible that the economic returns from using biochar may be higher than that from using lime after accounting for any other non-pH related plant growth benefits or carbon offset credits, were they to be available to farmers.

[2] This refers to Quincy sand soil type. The biochar requirement to raise the pH by a unit depends on the type of char used, e.g., switchgrass, digested fiber, bark, etc. Assuming an average pH increase across the chars of 0.058 pH unit/ton of biochar, it would require about ~17.24 tons of biochar to increase the soil pH by 1 unit.

3. Biochar carbon sequestration—related studies, policy, and programs

Biochar is produced through the process of pyrolysis. The three main products of pyrolysis: liquid (bio-oil), biochar, and gas, can influence the global carbon (C) cycle in two ways. First, all three pyrolysis products may be used as an energy source that can displace fossil energy use. Second, if the carbon-rich and stable biochar is produced from a biomass feedstock that removes carbon dioxide (CO_2) from the air via photosynthesis, which would otherwise have decomposed, then char-amended land becomes a carbon sink for more intensive and long-lasting carbon storage.

Lehmann et al. (2006) estimated an annual sequestration of 0.2 Pg C (200 million metric tons) through slash-and-char (instead of slash-and-burn) and biochar application to the soil. Furthermore, the study reported that low-temperature pyrolysis of biomass combined with the capture of gas and liquid products for bioenergy production and soil application of biochar, could sequester the equivalent of about 10% of the annual US fossil-fuel emissions.

Laird (2008) proposed a national system of distributed fast pyrolyzers for converting biomass into bio-oil, gas, and char. Similar to Lehmann et al. (2006), he assumed that bio-oil and gas are used as energy sources that can displace fossil fuel use, while char was applied to agricultural soils. Assuming the United States can produce 1.1 billion metric tons of biomass per year from harvestable forest and crop lands, the implementation of Laird's proposal could displace 25% of the nation's fossil fuel oil consumption per year. The study also estimated the aggregate carbon credit for fossil fuel displacement and biochar C sequestration to be 10% of the average annual US CO_2–C emissions.

The carbon content of biochar varies depending on the feedstock. Collins (2008) showed biochar carbon content (from slow pyrolysis) ranging from 61% to 80%, the highest being from wood pellets (Table 2). Woody feedstocks (bark, wood pellets) tended to have a higher carbon content compared to herbaceous feedstocks (switchgrass, digested fiber). Based on these figures, approximately 0.61–0.80 MT of carbon (or 2.2–2.93 MT of CO_2)[3] is sequestered for every ton of biochar applied to the soil.

Incentives for greenhouse gas mitigation such as carbon market offset credits may tip the scale in favor of biochar as a soil amendment rather than as a renewable energy source. At the international level, the Kyoto Protocol under the United Nations Framework on Climate Change (UNFCCC) only allows C sequestration from afforestation and reforestation in the trading program established under the Clean Development Mechanism (CDM) (UNFCCC-CDM, 2009). Carbon sequestration in agricultural crops and soils is not currently eligible under CDM (Lehmann et al., 2006; FAO, 2009). In the United States, the Chicago Climate Exchange (CCX) has developed standardized rules for soil carbon management offsets in the agricultural sector. Eligible projects are conservation tillage and grass planting, which have to be enrolled with a CCX-registered Offset Aggregator.

[3] To convert from carbon to carbon dioxide, multiply by 44/12 (~3.67) (Blasing et al., 2004).

In 2008, prices of traded CO_2 offsets on the Chicago Climate Exchange were volatile, ranging from \$1 to \$7.40/MT CO_2 (CCX, 2008). During the same year, the market prices of CO_2 offsets in the European Climate Exchange varied between \$17 and \$31/MT CO_2 (ECX, 2008). The differences in price across markets are in part due to the fact that participation in the CCX is currently optional; no entity is legally required to participate in this exchange. However, recent policy discussions at the national level suggest increased momentum toward a binding national carbon market. In the following section, we estimate the value of biochar as an input in crop production and as an instrument in C sequestration. We assume that a carbon market exists for avoided emissions and C sequestration due to use of biochar as soil amendment. Also, for the value of potential CO_2 offset, we use a low and high value of \$1 and \$31/MT CO_2.

4. Estimated costs and returns for using biochar as a soil amendment

In this section, we estimate the value of biochar as a soil amendment and the economic returns to farmers under a set of assumed conditions. The calculation is done in two stages. First, we assess: (a) the avoided emissions from the soil application of biochar instead of agricultural lime, excluding the energy and emissions from transporting and spreading the material; and (b) the amount of carbon sequestered from biochar application. Combined, the emissions avoidance and sequestration effects are counted as CO_2 offsets that can be sold under an assumed set of carbon offset prices. Second, we calculate the profit of crop production given two scenarios—without biochar but with lime application to the soil, and with biochar application as a substitute for lime. We focus on dryland wheat production in the state of Washington as a case study.

4.1. Estimates of avoided emissions

Gaunt and Lehmann (2008) and McCarl et al. (2009) estimated the avoided greenhouse gas emissions of applying biochar to agricultural land in terms of reduced agricultural input requirements due to a crop's improved use of nutrients. This translates to reductions in both fertilizer use and nitrous oxide emissions in fertilized fields. However, the dynamics of the relationship between fertilizers and biochar are not included in our analysis since the effects of biochar on the utilization intensity of fertilizers depend on various factors like the type of crop studied, soil type, soil quality, and biochar type. On the other hand, there is strong consensus about biochar's positive effects on soil pH that is similar to liming effects, as exemplified by studies discussed in Section 2.

Agricultural lime is commonly applied to soils to ameliorate the soil pH. The recommended rates of lime application in western Washington range from 2.28 to 11.35 MT/ha every 3–5 years, roughly.[4] Less or no lime is needed in Washington east of the Cascades because the native soil pH is high.[5] However, some soils in eastern Washington with a long history of urea or ammonium-based nitrogen fertilizers have experienced a reduction in pH to a low enough level to justify the need for lime. When there is a soil acidity problem, lime applications range from 2.28 to 6.8 MT/ha.[6]

West and McBride (2005) estimated the net CO_2 emission from application of agricultural lime at about 0.059 MT C (or 0.22 MT CO_2) per ton of limestone, based on the chemical reaction of lime in the soil and transportation of lime-derived bicarbonates to the ocean (via leaching and precipitation). This is the amount of emissions that can potentially be avoided by replacing lime with biochar. Using the CO_2 offset price range of \$1 to \$31/MT CO_2, the value of avoided emissions amounts to \$0.22–\$6.82/MT lime.

4.2. Estimates of biochar carbon sequestration

Biochar from herbaceous and woody feedstock sources are found to have a carbon content of 60.5–66.7% and 74.5–80%, respectively. We can assume from these figures that for every ton of biochar applied to the soil, 0.61–0.80 ton of carbon (equivalent to 2.2–2.93 ton of CO_2) can be sequestered (Collins, 2008). Using the highest carbon content of the wood-based biochar (i.e., 80%) and the CO_2 offset price range, the approximate value of biochar C sequestration is \$2.93–\$90.83/MT biochar.

4.3. Costs and returns of crop production

We examine the potential economic returns to farmers if they utilize biochar as a substitute for agricultural lime under three price scenarios: (a) \$114.05/MT based on the energy content of a wood-based biochar; (b) \$87/MT; and (c) \$350.74/MT. The first value represents the opportunity cost of the foregone use of biochar as energy source. A wood-based biochar has an average energy content of 12,500–12,500 BTU/lb (Dynamotive Energy Systems, 2007). The energy content of Central Appalachian coal is 12,500 BTU/lb and its price is \$116.38/MT as of 2008 (EIA, 2009). Using the energy content as basis, the combustion value of biochar is 98% that of Central Appalachian coal, or \$114.05/MT. The latter two prices are adopted from the estimated break-even prices of biochar in Granatstein et al. (2009).

Wheat, a key economic crop in Washington that covers about 930,000 hectares of land (NASS, 2010), belongs to a group of crops that can tolerate slightly acidic (i.e., 6.0–6.5) soil pH (CPHA, 2002). In general, wheat tends to favor soil pH between 6 and 7 (Beegle and Lingenfelter, 2005). Eastern Washington has experienced a decline in soil pH due to the use of ammonium-based fertilizers. We focus on changes in winter wheat yield in eastern Washington given changes in the soil pH as a case study, hypothesizing that if biochar could be used to address the pH problem and to sequester carbon, these combined values might justify its use on a large agricultural area. The crop yield is estimated through the following equation adopted from Mahler (1986):

$$\text{Winter Wheat Yield} = -2960.56 + 1530\ \mathit{SOILPH} \tag{1}$$

where *winter wheat yield* is in kg/ha, and *SOILPH* refers to the value of the soil pH of Palouse silt loam. Assuming the base soil pH of 4.5 for this soil type from Collins (2008), increasing the soil pH to 6 would require 6.48 MT of limestone per hectare (CPHA, 2002) or 76.53 MT of biochar per hectare (Collins, unpublished data).[7]

Using Eq. (1) with soil pH of 4.5, wheat yield is estimated at about 3924.44 kg/ha. On the other hand, with a soil pH of 6, the estimated wheat yield is about 6219.44 kg/ha. Profits from winter

[4] Data from personal communication with Craig Cogger, Washington State University, 2009.

[5] Data from personal communications with Richard Koenig, Craig Cogger and Joan Davenport, Washington State University, 2009.

[6] Data from personal communication with Joan Davenport, Washington State University, 2009.

[7] Note that the impact of char on soil pH depends on the soil type and the type of char. For the Palouse silt loam soil type, an average pH increase across the chars is ~0.0196 pH unit/ton of biochar per hectare. Based on this, it would require about 76.53 tons/ha to increase the soil pH from 4.5 to 6 (i.e., increase by 1.5 units).

Table 3
Comparison of profits from winter wheat production[a] (US$ per hectare), with and without biochar application.

Scenario	Revenue	CO_2 offset value[b]	Total cost[c]	Cost of ag lime[d]	Cost of biochar[d]	Profit[e]
Without biochar or agricultural lime application	$1099	–	$1038	–	–	$61
With ag lime application	$1741	–	$1038	$334	–	$369
With biochar application, *when offset price is $1/MT CO_2 and the price of biochar (P_B) is*						
P_{B1}=$350.74/MT[f]	$1741	$226	$1038	–	$26,842	−$25,913
P_{B2}=$114.05/MT[g]	$1741	$226	$1038	–	$8728	−$7799
P_{B3}=$87/MT[f]	$1741	$226	$1038	–	$6658	−$5729
With biochar application, *when offset price is $31/MT CO_2 and the price of biochar (P_B) is*						
P_{B1}=$350.74/MT[f]	$1741	$6995	$1038	–	$26,842	−$19,144
P_{B2}=$114.05/MT[g]	$1741	$6995	$1038	–	$8728	−$1030
P_{B3}=$87/MT[f]	$1741	$6995	$1038	–	$6658	$1040

Figures for the revenue, CO_2 offset value, cost and profit are rounded to the nearest whole number.

[a] The assumed base soil pH is 4.5. Biochar or agricultural lime application is intended to raise the assumed soil pH to 6.

[b] CO_2 offset value=225.66 MT of CO_2 offset per ha from avoided emissions of lime and biochar C sequestration (see Appendix) *times* the price of CO_2 offset ($1 or $31/MT CO_2).

[c] From 2008 Enterprise Budget for Eastern Whitman County, Conventional Tillage (Painter et al., unpublished). To illustrate the estimation of a farmer's profits with and without ag lime or biochar application, we chose Eastern Whitman County as example based on Mahler et al. (1985). The study found that the pH of soils in eastern Washington had significantly declined. By 1980, more than 65% in Whitman County had a soil pH less than 6.

[d] Excludes the cost of applying lime or biochar to agricultural land (machinery and labor cost).

[e] Profit=Revenue+CO_2 offset value−Total Cost−Ag Lime Cost−Biochar Cost. All are in US$ per hectare.

[f] Obtained from Granatstein et al. (2009).

[g] Based on the energy content of a wood-based biochar.

wheat production, with and without the application of biochar, are calculated as follows:

Without biochar or agricultural lime

$$\text{Profit}_1 = P_W Q_1 - \text{Total Cost} \tag{2}$$

Without biochar, with agricultural lime

$$\text{Profit}_2 = P_W Q_2 - \text{Total Cost} - P_L \times AGLIME \tag{3}$$

With biochar, without agricultural lime

$$\text{Profit}_3 = P_W Q_2 + COFFSET - \text{Total Cost} - P_{Bi} \times BCHAR \tag{4}$$

where P_W refers to the Fall 2008 contract price of winter wheat, which is $0.28 per kilogram (Union Elevator, 2008)[8]. Q_1 is the estimated yield of winter wheat given a soil pH of 4.5 in Eq. (2) and Q_2 in Eqs. (3) and (4) is the estimated wheat yield given a soil pH of 6. The product of P_W and Q gives the *revenue* in Table 3 below. P_L is the price of lime at $51.53/MT for a 100 lb bag in 2008.[9] *AGLIME* refers to the application rate of agricultural lime (6.48 MT/ha); P_B means the biochar price; *BCHAR* represents the application rate of biochar (76.53 MT/ha); and *COFFSET* is the value of carbon offset from avoided emissions and biochar C sequestration by replacing lime with biochar. Total Cost denotes the sum of fixed cost and variable cost of winter wheat crop production based on the Eastern Whitman County 2008 Enterprise Budget (Painter et al., unpublished), exclusive of lime or biochar cost.

Table 3 shows the estimated profits given the addition of agricultural lime or biochar to the soil and different price scenarios. As discussed above, the yield of wheat is higher when the soil pH improves; hence, the revenue is higher with the application of lime or biochar than without.

A farmer will gain a profit even when there is an additional cost of agricultural lime. When biochar replaces agricultural lime, on the other hand, getting a profit or a loss will depend on the price of biochar and value of sequestered carbon. Without a carbon offset market (COFFSET is zero in Eq. (4)), the price of biochar has to be about $9.19/MT in order for a farmer to break even (profit=0)[10] and about $4.82/MT for profit to be equal to that of agricultural lime scenario, excluding the transportation and application costs of biochar.

Suppose now that a carbon offset market exists. At $1/MT CO_2, the farmer loses income given any of the biochar price scenarios; and at $31/MT CO_2, losses are also incurred if the price of biochar is high, i.e., at $351 or $114/MT. This means that the income from offsets is not enough to support the adoption of biochar in agricultural production. If, however, the price of biochar goes down to $87/MT and the carbon offset is priced at $31/MT CO_2, a profit is gained and it is higher than the case where agricultural lime is used instead. This implies that when the price of biochar is low enough, the income derived from carbon offsets can outweigh the cost of biochar. It should be noted that the production cost does not include the cost of transporting and applying lime or biochar to agricultural land (machinery and labor cost). Including these would likely further drive up the estimated losses or decrease any profit earned.

The differences in potential profit given varying prices of biochar and carbon offset are further illustrated in Fig. 1. Profit declines as the price of biochar increases, holding other things constant. When the carbon offset price is $31/MT CO_2, the farmer will break even if the price of biochar is approximately $100.73/MT. The farmer's estimated profit with biochar application will be equal to the profit with agricultural lime application ($369/ha) if the price of biochar is about $95.91/MT. On the other hand, at a carbon offset price of $1/MT CO_2, a profit of about $163.70/ha is gained when the price of biochar is $10/MT. At this lower offset price, the farmer will break even if the price of biochar is approximately $12.14/MT.

Another issue to consider is that the carbon price (P_{carbon}) based on a cap and trade system may be correlated in varying ways to different energy sources, depending on the carbon content of the energy source (Mansanet-Bataller et al., 2007; Koenig, 2011). Given this potential relationship between the two prices, it is worthwhile considering a breakeven relationship between them. We rely on coal and coal price (P_{coal}) as the basis

[8] 1 bushel of wheat=27 kg of wheat (Smith, 2007).

[9] Data from personal communication with Steve Eckhart, J.A. Jack and Sons, 2009.

[10] From Eq. (4), the price of biochar (P_B) at which profit is zero is derived by calculating: $P_B=(P_WQ+COFFSET-\text{Total Cost})/BCHAR$.

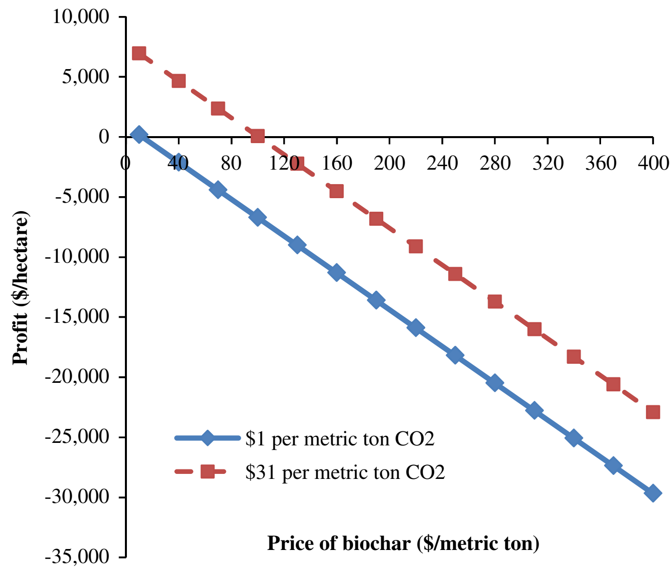

Fig. 1. Profit given the low/high price of CO_2 offset and different prices of biochar.

for our biochar energy value calculations. Based on Eq. (4), the relationship between biochar application and carbon application, and biochar application rates (discussed in the Appendix, and holding wheat revenues and production costs constant), it can be shown that profits are positive if

$$P_{carbon} > -3.12 + 0.34 P_B \quad (5)$$

If the price of biochar is driven largely by its energy content as embodied in coal, then P_B will be $0.98 P_{coal}$, so making this substitution, we have

$$P_{carbon} > -3.12 + 0.33 P_{coal} \quad (6)$$

Based on this equation and a coal price of $116.38, the carbon price would have to be at least $35.30. If these two prices are positively correlated, then the price of carbon would have to increase (or decrease) $0.33 per dollar increase (or decrease) in the coal price in order to ensure positive profits. If profits are negative (as in Table 3 with biochar price based on energy content), then co-movement in the two prices may mean that biochar application may be unprofitable for large ranges of these prices.

Perhaps surprisingly, Mansanet-Bataller et al. (2007) find no statistical relationship between the rate of change in coal and carbon prices, which suggests that our *ceteris paribus* comparisons are not unreasonable to pursue. However, if a positive relationship between these two prices were to exist, then a positive profit may be received even if energy prices increase.

5. Conclusions

Our quantitative analyses focus on using biochar as a soil additive and its potential carbon sequestration benefits for agricultural uses. We find that biochar soil application can be economically feasible given the following scenarios:

- If there exists a carbon market that recognizes the avoided emissions and carbon sequestration due to the application of biochar to agricultural soils. This is a necessary condition if biochar will be promoted as a technology for carbon sequestration; and
- If the market price of biochar is low enough so that a farmer will earn a profit after applying biochar to the crop field (i.e., in our case study, lower than $12.14 and $100.73/MT when the price of carbon offset is $1 and $31/MT CO_2, respectively).

It is clear that biochar has potential as a soil amendment and its value as such would likely increase as social and regulatory interest in carbon sequestration increases because of the longevity of carbon in the soil. However, more substantial increases in crop production need to be documented across a range of crops and soils that can add value to the farm at a level beyond the estimated value of biochar for carbon sequestration. Under the current economic situation, growers are unlikely to adopt biochar use without greater payback. Also at this time, even if growers found biochar beneficial, they could face difficulty in sourcing quantities large enough for farm application.

Many niche opportunities for biochar use are also possible, including soil amendment and compost use outside of agriculture such as urban gardens, lawns, parks, and ball fields. Biochar can be suitable as a precursor to activated carbon commonly utilized in industrial filtration process (Azargohar and Dalai, 2006) like municipal wastewater treatment (e.g. Bansode et al., 2003; Ng et al., 2003) and other water and air filtering systems (Kearns, 2008; Lima et al., 2008). Biochar can also be used as an energy source; as combustion fuel to power the pyrolysis process; as a gasifier feedstock (Boateng, 2007; Polagye et al., 2007); or for water heating and cooking (IBI, 2009; Johannes, 2008). The extent of developing these markets, of course, depends on many factors associated with the cost of biochar production relative to existing alternatives, as well as the relative effectiveness of biochar from pyrolysis for intended uses. The question is whether or not it would be more economically valuable to use biochar as a soil amendment rather than for energy production or other alternative uses. For instance, it may be more economically attractive to burn it to generate energy (i.e., as a substitute for coal) if the energy content of biochar is high. However, the process loses the added benefits of applying biochar to soils, such as gains in agricultural productivity due to soil quality improvement and payments for carbon sequestration.

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Appendix

Assumptions used to calculate the value of CO_2 offset

1. Case study: Eastern Whitman County, Washington State, USA - a high precipitation region (more than 45.72 cm per year)
2. Type of soil: Silt loam. We use the base pH=4.5 in Collins (2008) for Palouse silt loam. To increase the soil pH of silt loam by 1.5 units (i.e., from 4.5 to 6), the requirements are:
   - 6.48 MT of agricultural lime per hectare (ha)[11]; or
   - 76.53 MT of biochar per hectare.[12]

[11] Source: California Plant Health Association (2002).

[12] Source: H. Collins, unpublished data. Palouse Silt Loam Soil Analysis, Biochar Analyses.

3. Emissions avoidance and carbon sequestration from using biochar as soil amendment:
   - Avoided emissions for not using lime = 0.22 MT CO_2 per metric ton of limestone.[13]
   - Biochar C sequestration = 0.8 ton/MT of carbon or 2.93 MT CO_2[14] per metric ton of biochar applied to the soil.[15]
4. Estimated carbon sequestration per hectare (CO_2 offset per hectare) given application of biochar to cropland:
   - Avoided emissions for not using lime = 6.48 MT lime per ha $\times$ (0.22 MT CO_2/MT of lime) $\approx$ 1.43 MT CO_2/ha.
   - Biochar C sequestration = 76.53 MT biochar per ha $\times$ (2.93 MT CO_2/MT of biochar) $\approx$ 224.23 MT CO_2/ha
   - Total value of CO_2 offset $\approx$ 225.66 MT CO_2/ha

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[13] Source: West and McBride (2005).

[14] To convert from carbon to carbon dioxide, multiply by 44/12 ($\sim$3.67) (Blasing et al., 2004).

[15] Based on biochar content of pine pellets. Source: Collins, 2008.